Fourth International Workshop on

EXPERT EVALUATION & CONTROL OF COMPOUND SEMICONDUCTOR MATERIALS & TECHNOLOGIES

EXMATEC 98

CONFERENCE PROGRAMME, ABSTRACTS & EXHIBITION GUIDE

The Trevithick Building
Cardiff School of Engineering
University of Wales, The Parade, Cardiff, Wales

21st to 24th June, 1998

The Exmatec '98 meeting is sponsored by the Applied Solid State Chemistry Group of the Royal Society of Chemistry and the British Association for Crystal Growth, Wafer Technology Ltd, I.E.M. Technologies Ltd, Chell Instruments Ltd, Bede Scientific Instruments Ltd and the U.S. Army European Research Office

FOURTH INTERNATIONAL WORKSHOP
on
EXPERT EVALUATION AND CONTROL OF COMPOUND SEMICONDUCTOR MATERIALS AND TECHNOLOGIES

EXMATEC '98

CARDIFF UNIVERSITY

21ST TO 24TH OF JUNE, 1998

Organized by the Cardiff School of Engineering and Epitaxial Products International Inc

CHAIRMAN'S FOREWORD

Welcome to EXMATEC '98 and to Cardiff, the capital city of Wales. We hope that you will find the workshop entertaining and productive and that you will enjoy your stay in our city. We have put together an interesting and stimulating programme of presentations from researchers as far afield as Japan and the USA, and we would like to thank those of you who are presenting papers for your contribution to the workshop.

The research presented at the conference will be published in a special issue of Materials Science and Engineering: B by Elsevier and we would like to thank the Guest Editors Ali Rezazedah and Garth Swanson for their assistance. We are also grateful to the members of the Programme Committee and other colleagues who kindly agreed to referee the papers for the proceedings.

In addition we would like to give a special thank you to our sponsors who have graciously provided financial support to the workshop. Their support has enabled us to provide you with a number of special extras that we are sure will make a real difference to your enjoyment of the workshop.

We have organised what we hope is a fairly relaxed but enjoyable social programme and we would like to invite you all to participate in these activities. All registered delegates and accompanying persons are invited to attend the conference dinner and pre-dinner drinks which will be held in the Park Hotel in central Cardiff on Tuesday evening, and the excursion to Techniquest in Cardiff Bay on Monday evening, which includes a drinks reception sponsored by Bede Scientific Instruments Ltd.

Please note that the registration desk will be staffed at all times during the workshop and the staff are there to help you so please do not hesitate to ask for assistance with accommodation, workshop arrangements or information on Cardiff and the surrounding area.

We wish you a successful EXMATEC '98 and a pleasant stay in Cardiff.

Roy Blunt
Chairman
On behalf of the Organizing Committee

CONFERENCE INFORMATION

CONFERENCE LOCATION

The conference sessions will all take place in the Trevithick Building, Cardiff School of Engineering, The Parade, Cardiff. A registration desk will be set up in the foyer and will be staffed throughout the conference. The technical sessions will take place in the Faculty Lecture Theatre on the 2nd Floor. The exhibition will be located in the Junior Common Room to the left of the Registration Desk. The poster sessions will be held in Seminar Rooms 1 and 2 on the Ground Floor. Morning and afternoon teas will be served in the Junior Common Room and lunch will be available in the Refectory to the right of the Registration Desk.

POSTER SESSIONS

The poster sessions will be held on Tuesday in Seminar Rooms 1 and 2. Velcro and scissors will be available from the Registration Desk and you should set up your poster well before your designated poster presentation. Ask at the registration desk for further assistance.

SOCIAL PROGRAMME

The social programme will start with a light buffet on Sunday evening at 5pm in the Junior Common Room. On Monday evening there will be a drinks reception sponsored by Bede Scientific Instruments at Techniquest, a hands on science museum in Cardiff Bay, and on Tuesday a conference dinner at the Park Hotel in Park Place. All delegates and any accompanying persons are invited to these events.

PUBLICATION OF PAPERS

Final papers may be submitted at the conference. Please hand them to the Registration Desk. If you do not have your final paper with you then please send it to Cherrie Summers at the following address as soon as possible and not later than 10 July:

PO Box 917
Newport Rd
Cardiff CF2 1XH

ACKNOWLEDGEMENTS

The local organizing committee wishes to thank the following organisations for the considerable support provided to EXMATEC '98.

Applied Solid State Chemistry Group of the Royal Society of Chemistry
British Association for Crystal Growth
Wafer Technology Ltd
IEM Technologies Ltd
Chell Instruments Ltd
US Army European Research Office
Bede Scientific Instruments Ltd

EXMATEC '98

Fourth International Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies

Cardiff, Wales 22nd - 24th June 1998

Programme

Workshop Programme

Sunday 21st June

5 p.m. Registration, Trevithick Building, The Parade, Cardiff

Monday 22nd June

8.30 a.m. Registration, The Trevithick Building, The Parade, Cardiff

Session 1, *Substrates* 8.50 a.m. - 10.30 a.m. Chair : R. Blunt	**Presenter**
8.50 Welcome and Introduction	
9.00 Latest developments in VGF technology: GaAs, InP, and GaP	M Young
9.30 Photoelastic characterisation of residual strain in GaAs, wafers annealed in different holder geometrics	M Herms
9.45 Non destructive Mode index Measurement using Resonant Coupling	C Miner
10.15 X-ray Characterisation of InP Substrates	B Tanner

10.30 a.m. Coffee Break and Exhibition

Session 2, *Reliability and failure analysis issues* 11.00 a.m. - 12.30 p.m. Chair : H. Thomas	
11.00 Reliability issues due to hot electrons in GaAs and InP HEMTS	R Menozzi
11.30 Optical and structural analysis of degraded high power InGaA1As/As/A1GaAs lasers	C Frigeri
11.45 Failure analysis of heavily proton irradiated p+-n InGaP solar cells by EBIC and cathodoluminescence	M Romero Florez
12.00 Electron irradiation and thermal annealing effects on GaAs solar cells	X Xiang
12.15 Structural characterisation of InGaP/GaAs heterojunction bipolar transistors	T Martin

12.30 p.m. Lunch and Exhibition

Session 3, *Widebandgap materials* 2.00 p.m. - 4.00 p.m. Chair : W. Jantz	
2.00 III-Nitrides for Red and IR applications	C Abernathy
2.30 Large area GaN substrates	O Kryliouk
2.45 Structural characterisation of InGaN/GaN layers by transmission electron microscopy	D Cherns
3.15 Point defect characterisation of GaN and ZnO	D Look
3.30 Optical mapping of the net donor concentration in n-type SiC	A Winnaker
3.45 Characterisation of deep level trap centres in 6H-SiC pn junction diodes	Guillot

4.00 p.m. **Tea and Exhibition**

4.30 p.m **Panel Sessions: Characterization for the year 2000**

6.15 p.m. **Bus leaves Trevithick for Techniquest visit and Bede Scientific Drinks Reception**

7.30 p.m. **Bus returns from Techniquest to Trevithick Building**

Tuesday 23rd June

Session 4, *Characterisation and monitoring I* 8.30 a.m. - 10.30 a.m. Chair : S. Krawczyk

8.30 In-line and in-situ monitoring and control of semiconductor alloy device structures using spectroscopic ellipsometry	C Pickering
9.00 Optimisation of experimental conditions for variable angle spectroscopic ellipsometry. Application to GaAs quantum well characterisation	S Colard
9.15 Real-time strain monitoring in thin film growth. Cubic Boron Nitride on Si (100)	R Clarke
9.30 The use of laser interferometry for MOCVD process control	A Stafford
9.45 Luminescence imaging - a well established technique to study material - and device - related problems	M Baeumler
10.15 An optical study of the properties of AlGaInP epitaxial layers with varying composition and GaAs substrate orientation	G Jones

10.30 a.m. Chell Sponsored Coffee Break and Exhibition

Poster Session A   11.00 a.m. - 12.30 p.m.

12.30 Lunch and Exhibition

Session 5, *Characterisation and monitoring II* 2.00 p.m. - 3.30 p.m. Chair : R. Wallis

2.00 Characterisation of HBT material	E Richter
2.30 Contactless electroreflectance characterisation of GaInP/GaAs HBT structures	I Calder
2.45 InGaP/GaAs based HBT characterisation using non contact electro-optic diagnostic tools	M Murtagh
3.00 Production characterisation of III/V epilayers	C Meaton

3.30 p.m. Afternoon Tea

Poster Session B   4.00 p.m. - 5.00 p.m.

7.30 p.m. Drinks Reception at the Park Hotel, Park Place, Cardiff

8.00 p.m. Conference Dinner at the Park Hotel, Park Place, Cardiff
Entertainment sponsored by IEM Technologies

Wednesday 24th June

Session 6, *Materials, processing, and growth issues* 8.30 a.m. - 10.30 a.m. Chair : C. Frigeri

8.30 The upper limits of useful n- and p- type doping of GaAs and A1As	R Newman
9.00 Non-annealed ohmic contacts to p-GaSb grown by molecular beam epitaxy	A Vogt
9.15 Hydrogenation of buried passive sections in photonic circuits. A tool to improve propagation losses at 1.56μm	E Rao
9.30 Higher yield of 1.55μm lasers through MOVPE growth under N_2 atmosphere with excellent homogeneity	E Kuphal
9.45 Materials issues in GaInP laser diodes	P Blood
10.15 Low temperature silicon nitride for InP HBT	J Courant

10.30 a.m. Coffee

Session 7, *Characterisation and monitoring III* 11.00 a.m. - 12.30 p.m. Chair : D. Look

11.00 Electrical characterisation of III/V semiconductors using scanning capacitance microscopy	A Erickson
11.30 Characterisation of surface states density and substrate/ epilayer interface states in pseudomorphic A1GaAa/InGaAs/GaAs heterostructures	V Mosser
11.45 Assessment and the impact of structural parameters and device technology on resonant tunnelling diode characteristics	W Prost
12.00 Photoreflectance as a non-destructive room temperature technique for routine testing of PM-HEMT structures	P Panayotatos
12.15 Photoreflectance evaluation of MOVPE A1GaAs/GaAs multiple quantum wells on (111)A GaAs	A Majerfeld

12.30 a.m. Lunch

2.00 p.m. Close of Conference

Poster Session A	**Presenter**
Characterisation of III-V Oxide Desorption by surface photoabsorption	D A Alwood
Magnetoplasma resonances in microstructures with two-dimensional electron Gas at 77K	T Baturina
Investigation of photo-stimulated diffusion for creation of thin doped layers in III-V semiconductor compounds.	N Dolidze
Scanning probe microscopy characterisation of surface semiconductor nanostructures.	V A Fedirko
Multiple quantum wells GaAs/A1GaAs solar cells : Transport and recombination properties by means of EBIC and Cathodoluminescence.	D Araujo Gay
Comparison of GaAa/InA1As electroabsorption Modulator structures on (100) and (111) InP Substrates	A Georgekilas
InGaAs layers of high quality grown on patterned GaAs substrates with trenches.	Y Hayakawa
Contactless mapping of Mesoscopic resistivity variations in semi-insulating substrates	W Jantz
Analysis of hopping conduction in device-like structures on nonstoichiometric molecular beam epitaxial GaAs.	P Kordos
Be diffusion in InGaAs, InGaAsP Epitaxial layers and across InGaAs/InGaAsP, InGaAs/InP Heterointerfaces.	S Koumetz
The change of rotation angular dependence (AD) of the second harmonic intensity of CdTe epilayers on GaAs (100) substrate at the initial stage of heteroepitaxy.	V I Liberman
Electrical and morphological properties of ordered $In_xGal_{-x}P$.	J Novak
Capacitance-voltage profiling of Inhomogeneous multiquantum well structures AlGaAs/GaAs.	V Ovsyuk
Study of dopant-dependant band gap narrowing in semiconductor devices.	V Palankovski
Influence of GaSb substrate qualities on the properties of GaInAsSb films grown by MOCVD.	R Peng
Microscopic Investigation of intimate metal -$In_xGa_{l-x}As$ dot contacts obtained at room and cryogenic temperatures.	F Peiro
Si_3N_4/Si Heterostructures used for field effect enhanced photoconductivity in PbS thin films.	I Pintilie
High precision reflectometry : A method to evaluate the performance of photonic components and circuits.	EVK Rao
Tfts in polycrystalline silicon : High performances obtained in unhydrogenated in-situ doped films - Study of density of traps.	H Sehil
Formation of n-p junctions in a p-type MBE HgCdTe film by low temperature electrical activation of implanted boron atoms.	N Talipov
Differential magnetoresistance method for the characterisation of electron and light-hole concentrations and mobilities in narrow-gap p-Type HgCdTe.	N Talipov
The effect of interfacial layer on the relaxation of CdMnTE/CdTe multiple quantum well structures in InSb substrates.	B K Tanner

Poster Session B	Presenter
Growth of Tl-Containing Compounds by Gas Source Molecular Beam Epitaxy	C R Abernathy
Non-alloyed ohmic contacts using MOCVD grown $InGa_{1-x}As$ on n-GaAs.	Farid Amin
Process optimisation of the reactive ion etching of gallium nitride in methylchloride/hydrogen using the orthogonal method.	M Dineen
SEM and AFM Characterisation of High-Mesa patterned GaAs and InP substrates prepared by wet etching.	P Elias
The use of Capitance-Voltage (C-V) Profiling to Investigate the High Field, Electron Capture Characteristics of the EL2 Centre in GaAs.	S Estill
Study of Silicon doped VGF-GaAs by DSL-Etching and LVM Spectroscopy.	C Hannig
Growth of $Hg_{1-x}(CD_{1-y}Zny)_xTe$ epilayers on (100) Cd_{1-y} ZnyTe/GaAs substrates by ISOVPE.	I Ishikawa
Ion implantation induced defects in Si implanted GaAs studies by variable energy positrons	A Knights
Photoemmission and Raman study of GaAs passivated in alcoholic sulfide solutions.	M Lebedev
Investigation of MBE grown GaAs/A1GaAs/InGaAs heterostructures.	R Melkadze
The measurement of substrate temperature in MBE System.	N.N. Mikhailov
The optical reflectance spectral method for the evaluation of crystal quality of CdTe films on and HgCdTe.	N Mikhailov
Preparation and characterisation of n- and p- type ytterbium doped in InP epitaxial layers.	J Novotny
Comparative Investigation of MBE and MOCVD PMHEMT Structures for high frequency. Applications.	P Panayotatos
Effect of thermal annealing in different ambient on photoelectrical properties of chemical Deposited CdS thin films.	D Petre
Effect of rare earth addition on liquid phase epitaxial InP and GaInAsP semiconductor layers.	O Prochaxkova
Networks of GaAs quantum wires : Preparation and Characterisation.	V Samuilov
Isoperiodical heterostructures GaInAsSb/GaSb LPE-grown from Sb-rich melts in spinodal decomposition area.	V Smirnov
Hydrogen plasma treatment of Germanium doped n-GaAs.	K Somogyi
Some comparison of properties of thick GaN layers grown on sapphire and silicon substrates by VPE.	K Somogyi
Enhancement of the performance of GaAs planar photoresistors by sulphur passivation of the surface.	K Somogyi
Precise measurement of the temperature dependence of the mobility at the first order phase transition in Ag_2Se layers.	K Somogyi
The study of spectral photoconductivity response of MCT heterostructures by contactless method.	VS Varavin
Assessment of carbon in polycrystalline gallium arsenide using SSMS, FTIR and CPAA	B Weidemann

EXMATEC '98

Fourth International Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies

Cardiff, Wales 22nd - 24th June 1998

EXHIBITION GUIDE

EXMATEC '98

Exhibition Stands

STAND 1	MATS UK
STAND 2	BEDE SCIENTIFIC INSTRUMENTS LTD
STAND 5	WEST ASSOCIATES (AMERICAN XTAL TECHNOLOGY)
STAND 7	OXFORD INSTRUMENTS PLASMA TECHNOLOGY
STAND 8	LEDA MASS LTD
STAND 9	JAPAN ENERGY
STAND 10	OXFORD INSTRUMENTS RESEARCH
STAND 12	NANOPROBE
STAND 13	PHILIPS ANALYTICAL
STAND 14	ELSEVIER SCIENCE
STAND 15	LOUGHBOROUGH SURFACE ANALYSIS LTD
STAND 16	WAFER TECHNOLOGY LTD
STAND 17	BIO-RAD MICROMEASUREMENTS LTD
STAND 18	EPITAXIAL PRODUCTS INTERNATIONAL
STAND 19	IEM TECHNOLOGIES LTD
STAND 20	CHELL INSTRUMENTS LTD

MATS (UK) LTD — Stand 1

MATS is an independent analytical laboratory near Warrington. We offer a commercial service for quantitative surface and interface analysis and materials characterisation, specialising in SIMS and SNMS. In addition to SIMS and SNMS we also offer a wide range of complementary techniques, including RBS, XPS, GDMS, ICPMS, Raman, FTIR, HRTEM, AFM and STM.

We serve the analytical needs of the manufacturing sector by solving quality control problems. We also provide support for Universities and Corporate Research Organisations worldwide by providing analysis and consultancy for their fundamental research and materials development projects.

Our laboratories are equipped with multi-technique SIMS instruments, complemented by a team of experienced scientists. This combination provides a fast, clear, unambiguous and confidential interpretation of results to solve a wide range of problems and provides answers to a variety of materials science issues.

The MATS (UK) Stand at EXMATEC '98 will show applications of SIMS and SNMS depth profiling to III/VI materials, including ultra-low detection levels of hydrogen, carbon, nitrogen and oxygen.

Contact: Mats (UK) Ltd, Innovation House, Daten Park, Leacroft Road, Birchwood, Warrington, A3 6UT. Tel : 44 (0) 1925 844777, Fax : 44 (0) 1925 844780, E Mail : info@mats-uk.com.

BEDE SCIENTIFIC INSTRUMENTS LTD — Stand 2

Bede is a leading global manufacturer of analytical X-Ray characterisation equipment, now celebrating its 20th anniversary. Bede's product line includes high resolution X-Ray diffractometers for R&D as well as quality control; the new Microsource® X-Ray generator; analysis software; and expert service.

For further information please come and visit us on Stand 2.

Contact: Bede Scientific Instruments Ltd, Headquarters, Bowburn South Industrial Estate, Bowburn, Durham, DH6 5AD. Tel : 44 (0)191 3772476, Fax : 44 (0)191 3779952, E Mail : info@bede.co.uk

WEST ASSOCIATES — Stand 5
(AMERICAN XTAL TECHNOLOGY)

West Associates acts as a European agent for AXT as well as some complementary gas handling products :

American Xtal Technology – Epiready GaAs & InP wafers, vertical gradient freeze grown for extremely low EPDS.

UltraPure – Point of use and bulk gas purifiers configurable for hybrids, inerts and a range of other gases.

CS Clean Systems – Dry bed gas scrubbers.

Emergency Containment Systems – Gas cylinder containment vessels, for pressure and vacuum tight storage and transport of hazardous gases.

All of these products can be seen at our website : www.westassociates.co.uk.

Contact: West Associates, 46 Leigh Road, Cobham, Surrey, KT11 2LD Tel : 44 (0)1932 868006, Fax : 44 (0)1932 860932, E Mail : westonweb@compuserve.com

OXFORD PLASMA TECHNOLOGY Stand 7

Oxford Plasma Technology is a leading supplier of plasma and ion beam processing equipment for the semiconductor industry. Products range from small stand alone units aimed at the R&D market to fully clustered cassette to cassette platforms for high throughput production processing. The Plasmalab range consists of seven models covering all major plasma technologies, including ICP and RIE, and the IonFab range consists of two models covering ion beam etching, chemically assisted ion beam etching and ion beam and ion assisted sputter deposition.

OPT has over 17 years experience in plasma and ion beam processing and is one of the worlds leading suppliers of plasma processing equipment to the compound semiconductor industry, with key processes developed for both the Opto and Microelectronics markets. The company maintains close collaborative links with both academia and industry and attributes much of its success in the compound semiconductor market to joint ventures into leading edge projects such as high density plasma etching of III-V materials and dry etching of Gallium Nitride and related compounds.

The company is based near Bristol, UK, and forms part of the Oxford Instruments Group which employs over 1500 people worldwide with an annual turnover of approximately £160 million plus a joint venture with Siemens of approximately £75 million. OPT has a 4000m^2 factory with on-site manufacturing., two clean rooms/laboratories for demonstration purposes as well as sales offices located throughout the world. The Applications laboratory is equipped with the latest systems and has facilities for demonstrating ICP, RIE or PE mode etching; PECVD of low stress layers and ion beam etching; sputter decomposition and chemically assisted ion beam etching.

Contact: Oxford Instruments Plasma Technology, North End, Yatton, Bristol, BS49 4AP
Tel : 44 (0)1934 833851, Fax : 44 (0)1934 834918, E Mail : bedwyr.humphreys@oxinst.co.uk

LEDA-MASS LTD Stand 8

JAPAN ENERGY/NIMTEC Stand 9

Japan Energy/NIMTEC supplies semiconductor materials ranging from high purity metals to compound semiconductor wafers and sputtering targets to customers the worldwide.

Japan Energy started as a mining and refining company almost 100 years ago. Based on its accrued knowledge and experience as well as its untiring R & D it is continuously providing the highest quality materials to semiconductor industries. guaranteed by using advanced technical instruments specially prepared for the quality assurance of semiconductor materials.

- ICP Atomic Emission Spectrometer
- ICP Mass Spectrometer
- Atomic Absorption Spectrometer Flame Atomizer
- Spectrophotometer
- Atomic Absorption Spectrometer Metal Atomizer
- Oxygen and Nitrogen Analyser
- Hydrogen Analyser Carbon Analyser
- X-Ray Fluorescence Spectrometer
- SEM and EDXS EPMA
- Spark Source Mass Spectrometer
- Auger Electron Spectrometer
- X-Ray Photoelectron Spectrometer
- Glow Discharge Mass Spectrometer

Japan Energy/NIMTEC's main products are as follows:

- Compound Semiconductor Wafers : InP,CdTe, Epitaxial Wafers (MBE,MOCVD)
- High Purity Metals : In(6N, 7N), Cd (6N, 7N), Te (6N, 7N), Cu (6N)
- Sputtering Targets : Ti, Al, WSi, Ni, Co, Cu, Ta, Au, Pt, Pd

Contact: Japan Energy Ltd (UK) Ltd, 39 Dover Street, London, W1X 3RB
Tel : 44 (0)171 6293602, Fax : 44 (0)171 4956349, E Mail : kotsuki@jais.co.uk

OXFORD INSTRUMENTS — Stand 10

Oxford Instruments is a leader in the field of design, manufacture and supply of specialist products for electron microscopy. We have particular expertise in the fields of cathodoluminescence (CL) and cryogenics, and we will be highlighting our products for characterizing semiconductors using CL, EBIC and helium stages.

CL together with EBIC can be used to characterize both the optical and electronic properties of devices at sub micron resolution. MonoCL 2 is a new CL system for high resolution CL imaging and spectroscopy over a wide spectral range. EBI Quant allows simultaneous quantitative EBIC linescans, area scans and images of the same devices. These techniques are particularly effective when applied at cryogenic temperatures, when the radiative recombinations of electron-hole pairs are maximized. Applications include analysis of quantum structures in materials developed for laser diodes, wide band gap materials such as GaN and also solar cell material.

Contact: Oxford Instruments, Research Instruments, Tubney Woods, Abingdon, Oxon. OX13 5QX.
Tel : 44 (0) 1865 393200, Fax : 44 (0) 1865 393333, E Mail : info.ri@oxinst.co.uk

NANOPROBE — Stand 12

Contact: 39 Rue Alain Chastien, France, 75015
Tel : 33 (0)142317441, Fax : 33 (0)142537632, E Mail : maurice.quillec@wanadoo.fr

PHILIPS MATERIAL CHARACTERISATION SYSTEMS — Stand 13

Philips Material Characterisation Systems (MCS) is part of Philips Analytical, a major supplier of analytical instrumentation for research and industry. Our instruments form a suite of characterisation tools covering the optical, structural and electrical properties of compound semiconductors. Our equipment improves epitaxial growth processes, increases yields and boost your profitability. Philips MCS products :

- Control the quality of your incoming substrates
- Rapidly optimise your growth conditions by providing fast feedback on epilayer composition and quality.
- Screen the uniformity of your epi-wafers
- Help estimate yields.

Our products are made with one purpose in mind - *to help our customers achieve better yields through better measurements.*

Contact: Philips Analytical, York Street, Cambridge, CB1 2QU
Tel : 44 (0)1223 374411, Fax : 44 (0)1223 374266, E Mail : sally.fuller@axr-cmb.be.philips.com

ELSEVIER ADVANCED TECHNOLOGY Stand 14

Elsevier Advanced Technology, publishers of III-Vs Review magazine, are presenting their range of market and technical information sources dedicated to the semiconductor industry worldwide. Free sample copies of III-Vs Review and information on the Advanced Semiconductors Buyer's Guide will be available.

Contact: **Elsevier Advanced Technology, P O Box 150, Kidlington, Oxford, OX5 1AS.**
Tel : 44 (0)1865 843848 or 843000, Fax : 44 (0) 1865 843971, E Mail : d.prosser@elsevier.co.uk

LOUGHBOROUGH SURFACE ANALYSIS Stand 15

Contact: **P.O. Box 5016, Unit FC, Gas Research and Technology Centre, Ashby Road, Loughborough, LE11 3WS. Tel : 44 (0)1509 283069, Fax : 44 (0)1509 283067,**
E Mail : D.E.SYKES@lsaltd.co.uk

WAFER TECHNOLOGY LTD Stand 16

Wafer Technology, based in Milton Keynes, offers the world's broadest range of III-V materials in a variety of forms and orientations. The company focus is on forming partnerships with its customers and on providing on time delivery of competitive quality, value for money products.

Contact: **Wafer Technology Ltd, 34 Maryland Road, Tongwell, Milton Keynes, Bucks, MK15 8HJ**
Tel : 44 (0)1908 210444, Fax : 44 (0)1908 210443, E Mail : klamb@wafertech.co.uk

BIO-RAD Stand 17

Bio-Rad Micromeasurements Systems are used throughout the world in the development, control and characterisation of state of the art semiconductor processes.

The range of equipment includes systems for profiling of carrier concentration (Electrochemical CV and Differential Hall), detecting contaminants (DLTS and PL) and measuring the electrical properties of wafers (Hall).

On show for the first time in Europe will be the new RPM2000 rapid photoluminescence mapper capable of spectral mapping a 2 inch wafer with 1mm spatial resolution (~2500 points) in less than 30 seconds.

Other systems available include the measurement of overlay error and critical dimensions. FTIR for epitaxial thickness and dopant concentration measurement is also available.

Contact: **Bio Rad Micromeasurements Ltd, Bio Rad House, Maylands Avenue, Hemel Hempstead, HP2 7TD, Tel : 44 (0) 1442 232552, Fax : 44 (0) 1442 391717, E Mail : sms_sales@bio-rad.com**

EPITAXIAL PRODUCTS INTERNATIONAL Stand 18

Epitaxial Products International is now firmly established as the world's foremost supplier of III-V epitaxial semiconductor structures for application in optoelectronic, optical, electronic and microwave applications. EPI provides the widest range of III-V materials capabilities from which customer specific structures are grown and characterised and guaranteed to meet customer specification.

The bulk of EPI's business is focused towards optoelectronic products. EPI is widely recognised as having the world leading position in this business sector, having developed an excellent reputation for first class research capabilities with short time to market; excellent development capabilities to fine tune products for mass production; and world class production processes from which large volume, low cost, epiwafer production business is serviced.

EPI only manufactures epitaxial wafers. It does not manufacture devices or any other down stream products that may compromise its confidential close working relationship with its key customers who are prominent players in the optoelectronics industry. Both customer specifications and customer identity are confidential to the extreme.

EPI's production capabilities encompass InP based structures for use in telecom emitters and detector applications, GaAs based edge emitting lasers and VCSEL structures, visible laser and visible high brightness LEDs, and some electronic products focused to high volume application such as HBT structures.

EPI's customers will be companies who can process such epitaxial wafers into devices and it is EPI's desire to establish a close working business partnership with companies who desire to address large volume chip and/or device manufacture with commitment.

Contact: Epitaxial Products International, Cypress Drive, St. Mellons, Cardiff, CF3 O5G
Tel : 44(0)1222 794422, Fax : 44 (0)1222 779929, E Mail : gjones@epitaxial-products.co.uk

I.E.M. TECHNOLOGIES LTD Stand 19

I.E.M. is dedicated to the provision of high quality products and services for the Semiconductor industry world-wide. The Company operates in three areas :

Air Pollution Control Plant Manufacture
The Company custom designs, manufactures and commissions, air pollution control plant for wafer fabs and many other Semiconductor applications. The Company has also undertaken a number of plant upgrades for increased efficiency or for refurbishment purposes. We have installed equipment at many of the world's leading Semiconductor plants.

Stainless Steel Installation Service
Using specialist orbital welding equipment, the Company offers a full installation service for stainless steel pipeworks, for hook ups, process gas lines, bulk gas lines, high vacuum systems and chemical piping systems.

Maintenance
We provide maintenance for Air Pollution control systems, plant installation, refurbishment, upgrade and removal. Pigging for stainless pipework.

Please visit our stand number 19 for further information.

Contact: I.E.M. Technologies Ltd, Manuflex House, Evercreech Way, Walrow Road Industrial Estate, Highbridge, Somerset, TA9 4AW. Tel : 44 (0)1278 795678, Fax : 44 (0)1278 795677, E Mail : IEMuk1@aol.com

CHELL Stand 20

Chell has many year's experience developing novel flow and pressure control systems for MOCVD process systems. The EPR in-line bubbler pressure controller on the Chell stand is a direct result of this work.

PlasmaChrom, also being shown, is a tristimulus optical chromaticity sensing instrument that has shown great promise as an in-situ process endpoint, film thickness and uniformity monitoring system.

In a technical and distribution link-up between Chell and SMC Pneumatics, several new products and process techniques have been developed. Amongst these is a novel exhaust pressure control system that provides pressure stabilities of 1 part in 10^3 and very fast slew rates, if required – all at a substantially lower cost.

Chell has provided a calibration and repair service for Mass Flow Meters and Controllers, together with Capacitance Manometers and pressure controllers for over 20 years. The latest developments in transfer standard performance are reflected in Chell's Table of Uncertainties which are only one step removed from the appropriate National Standard.

Contact: **Chell Instruments Ltd, Tudor House, Grammar School Road, North Walsham, Norfolk, NR28 9JH. Tel : 44 (0)1692 402488, Fax : 44 (0)1692 406177, E Mail : ron.mitchell@chell-instruments.co.uk**

FUTURE CONFERENCES in CARDIFF

HETEROSTRUCTURE TECHNOLOGY WORKSHOP

Cardiff, 13 – 15 September 1998

SEMICONDUCTOR AND INTEGRATED OPTO-ELECTRONICS CONFERENCE (SIOE 99)

Cardiff, 7 - 9 April 1999

For further information please contact Cherrie Summers, Cardiff School of Engineering, PO Box 917, Newport Rd, Cardiff, CF2 1XH, UK.

EXMATEC '98

Fourth International Workshop on Expert Evaluation and Control of Compound Semiconductor Materials and Technologies

Cardiff, Wales 22nd - 24th June 1998

Session 1

Substrates

Monday, 9.00 a.m – 10.30 a.m.

Chair : R. Blunt

Latest Developments in VGF Technology: GaAs, InP, and GaP

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Abstract

VGF technology produces the world's highest quality III-V semiconductors, including GaAs, InP, and GaP. The technology is playing an increasingly important role in the III-V semiconductor substrate industry. VGF is also the preferred technology in order to grow large-diameter crystals. The technique is now producing up to 6-inch diameter GaAs, 3-inch InP, and 3-inch GaP. The low thermal gradient and thermal dynamically-stable growth system allow the growth of these materials with the highest crystal quality. In this paper, we will report the recent progress in crystalline improvement, ion-implantation results, mechanical strength, and device data in the GaAs material. We will report the growth and characterization of VGF grown (100) InP ingots and wafers. We will also report the recent achievements of VGF grown GaP. More than two orders of magnitude reduction of EPD have been observed in the VGF-grown GaP as compared to the LEC grown materials. Preliminary results show up to ~10% increase in intensity for LEDs manufactured on these lower-EPD substrates.

Photoelastic Characterization of Residual Strain in GaAs Wafers Annealed in Different Holder Geometries

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The properties of semiconductor crystals used as substrates for microelectronic and photonic devices are usually homogenized and optimized by multi-step annealing procedures. Post-growth annealing is indispensible in order to reduce frozen-in residual strains for instance in view of subsequent loss-free sawing and polishing steps. The success of annealing is determined, on the one hand, by the thermodynamics of microdefects and strains but, on the other hand, by the thermal properties of all the set-up components. At present, most of substrates commercially available are ingot-annealed but wafer annealing has been under discussion to an increasing degree [1,2]. The free surface of a cylindrical wafer arrangement is up to 100 times larger than that of a cylindrical ingot of the same mass. Therefore, the wafer annealing arrangement interacts much more intensively to the vapour ambient than the ingot. The heat flow by thermal radiation is proportional to the radiating surface. More rapid heating-up and cooling-down steps are feasible. Consequently, multiple wafer annealing (MWA) seems to be more efficient and cheaper than ingot annealing. However, each wafer-holder configuration is more unsymmetrical and more non-uniform than an ingot. In this paper, we present photoelastic measurements on 2 inch GaAs wafers multi-step annealed in different holders as racks and rings made of quartz and graphite. By use of an high-sensitive scanning infrared polariscope (SIRP) [3] we have found that different holder geometries affect level and spatial distribution of residual strains. Thus, the SIRP maps of residual strain are suitable to provide information about the spatial distribution of temperature during MWA. Based on thermocouple measurements on wafer dummies of graphite the radial temperature gradients during heating-up and cooling-down steps will be additionally discussed. We conclude that inhomogeneities of the spatial distribution of microdefects and strains are mainly caused by the inhomogeneous distribution of temperature during heating-up and cooling-down steps.

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[2] O. Oda et al., *Proc. 10th IPRM*, Hyannis, MA (1997), 404-7.

[3] M.Yamada et al., *Proc. 8th Conf. Semi-Insulating III-V Materials*, Warsaw, (1994), World Scientific Publishing, 95-8.

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submitted to EXMATEC-1998, June 21-24, 1998, Cardiff, Wales, UK

NON-DESTRUCTIVE MODE INDEX MEASUREMENT USING RESONANT COUPLING

Carla Miner, Scott Campbell, Greg Pakulski and Kina Davitt

One of the challenges of the emerging dense wavelength division multiplexing optical communications market is the reliable targeting of emitters so as to precisely match closely spaced frequency grid points. In practical material terms, this translates into being able to monitor and control the mode index of a DFB laser cavity mid-way through the fabrication sequence so that the grating pitch can be adjusted appropriately.

A non-destructive method, based on resonant grating coupling, that satisfies the needs will be described. The method is demonstrated to have the accuracy and precision to measure mode index to 1 part in 10 thousand and a wavelength targeting accuracy of +/- 0.5 nm in the device manufacturing environment.

X-RAY CHARACTERISATION OF INDIUM PHOSPHIDE SUBSTRATES

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X-ray scattering techniques have been used to study the orientation, surface polishing and lattice perfection of (001) oriented LEC and VGF InP substrates. A novel method of determining precisely the wafer misorientation from the (001) plane using a combination of grazing incidence X-ray reflectivity and high resolution diffraction is described. Results are in excellent agreement with etching and optical methods. White beam X-ray topography showed that all VGF wafers except one had zero dislocation density, the exception having only a low density of approximately 200 cm^{-2}. This compared favourably with the LEC substrates where the dislocation density was up to 10^4 cm^{-2} in parts of the wafer. These dislocations, located in the four <100> quadrants, are associated with slip from the edges of the wafer. No growth striations were observed in the topographs of the VFG samples, in contrast to the LEC samples. Measurements of curvature were made by mapping the angular position of the Bragg peak as a function of position on the wafer and by step-scanning double axis X-ray topography. Results from the two techniques are in very good agreement , there being no systematic difference between the VGF and LEC wafers.

Symmetric reflection triple axis reciprocal space maps show that the lattice strain normal to the surface does not vary with sample preparation but that the tilt distribution does vary greatly. Grazing incidence specular and diffuse X-ray scattering measurements have been used to study variations in surface roughness. Excellent agreement between experimental and simulated data is achieved only when graded surface layers typically 30Å in thickness, and of higher density than the bulk material, are included. Figuring was found on all samples and the width of the specular peak in specimen-only scans rose as the width of the triple axis asymmetric 224 diffraction rocking curve increased. A similar relation was found between lateral correlation length and symmetric 004 rocking curve width.

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Session 2

Reliability and Failure Analysis Issues

Monday, 11.00 a m – 12.30 a.m.

Chair : H. Thomas

RELIABILITY ISSUES DUE TO HOT ELECTRONS IN GaAs AND InP HEMTs

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High Electron Mobility Transistors (HEMTs) play a major role in state-of-the-art microwave and millimeter-wave communication systems, which can benefit from their high cutoff frequency, low noise figure and large associated gain. Both AlGaAs/InGaAs Pseudomorphic structures (PHEMTs) on GaAs and InAlAs/InGaAs/InP HEMTs (either lattice-matched or pseudomorphic) are currently employed in Monolithic Microwave Integrated Circuits (MMICs) like low-noise and power amplifiers, oscillators, mixers, etc., operating well into the millimeter-wave frequency range. While GaAs PHEMTs have been a commercial reality for a few years, InP HEMTs are still more of a laboratory product, with good potentials in important niche markets like the military and aerospace. As is the case for other compound semiconductor technologies, a powerful boost is also expected in the next future due to the advent of widespread personal communication devices.

In both cases (GaAs and InP), quite a few papers have been published in the last 10-15 years on reliability issues, but the vast majority of them was focused on temperature-accelerated degradation mechanisms, such as ohmic or Schottky contact instabilities, carrier deconfinement due to dopant migration, etc.

Another important but sometimes overlooked reliability concern is the occurrence of hot electron (HE) and impact-ionization (II) conditions, due to the large electric field in the device channel. Such conditions are likely to develop in HEMTs because: i) in analog applications, the devices are biased in the saturation region, and the drain bias must be pushed up to get good output power; ii) in order to be operated at microwave and millimeter-wave frequencies, the HEMTs must have very short gates (typically $\leq 0.25\ \mu m$), which causes the peak channel electric field to soar to very high values even for relatively low drain bias; iii) for good carrier confinement, the channel layer must have a small bandgap, which favors impact-ionization; iv) the large electron mobilities that give HEMTs many of their attractive features also make the channel electrons quite easy to heat up. It is therefore very important to assess the reliability of HEMTs also from the standpoint of HE/II issues.

This paper will give an overview of this topic. First it will describe the physical phenomena taking place in the HEMT when HEs are created. This will introduce the main electrical and optical techniques for the detection and characterization of HE/II conditions: particular attention will be devoted to Electroluminescence measurements on GaAs and InP HEMTs for the important information they can provide. Next, the main device instabilities caused by HEs in GaAs PHEMTs and InP HEMTs will be described; these include threshold voltage shifts, breakdown walkout, transconductance and cutoff frequency degradation, and power slump. Finally, some indications will be given as to the main requisites for HE-robust HEMTs.

OPTICAL AND STRUCTURAL ANALYSIS OF DEGRADED HIGH POWER InGaAlAs/AlGaAs LASERS

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We have investigated the failure of high power lasers operated at elevated driving current beyond rollover, in order to stimulate and analyse degradation processes encountered during accelerated lifetime testing.

The MOCVD grown lasers, emitting at 808 nm, contained an InGaAlAs double quantum well (DQW) structure sandwiched between AlGaAs confinement and cladding layers. The investigation combined plan view RT photo-luminescence microscopy (PLM), cross-sectional transmission microscopy (TEM) in the dark field mode and X-ray microanalysis (TEM-EDX).

After degradation the laser facets were checked and found undamaged. Next, the devices were prepared for PLM investigation by removing the GaAs substrate with selective chemical etching [1]. Plan view images of the active area taken at 800 nm revealed sharply defined dark lines extending from the output laser facet in perpendicular direction (i.e. along <110>) into the inner part of the device. Outside of the dark lines the PL intensity appeared to be unchanged, indicating that laser performance degradation was exclusively due to these lines.

Cross-setional TEM specimens were prepared using the degraded device material, so that the dark lines intersected the specimen surface perpendicularly. Dark field imaging revealed nearly elliptic damaged areas of different sizes and excentricities, bisected by the active layer and extending symmetrically into both confinement layers. The original DQW structure was altogether destroyed within these areas. Instead of the two QWs separated by an AlGaAs barrier layer, just one thin line with dark TEM contrast was observed. Clearly the PL and laser degradation is due to this collapse of the DQW structure.

The likely assumption that the damage is due to an interdiffusion process was corroborated and clarified with TEM-EDX, showing that the elliptic area surrounding the destroyed QWs is devoid of Al, which in turn is found accumulated at its margin, where dark field TEM showed brighter contrast. Hence, the dissolution of the QW structure and the formation of the elliptic area are due to Al outdiffusion. Similar phenomena have been reported to affect the entire front facet area of ridge lasers [2]. We suggest that the outdiffusion is driven by temperature gradients of localized overheating in the active region which may be initiated by filamentation occurring at elevated laser power. Dislocations were observed by TEM in the transition region of undegraded to collapsed DQW, likewise indicating thermally induced local stress. The commencement of damage close to the output mirror indicates increased device temperature near the facet.

The laser diodes used in this study were kindly supplied by J. Luft, Siemens AG, Regensburg.

[1] M. Baeumler, J. L Weyher, S. Müller, W. Jantz, R. Stibal, G. Herrmann, J. Luft, K. Sporrer, and W. Späth. Proc. DRIP VII in Templin, Germany (1997)

[2] I. Rechenberg, U. Richter, A. Klein, W. Höppner, J. Maege, A. Klein, G. Beister, and M. Weyers, Inst. Phys. Conf. Ser. **157** (1997) 557.

Failure Analysis of Heavily Proton Irradiated p+ -n InGaP Solar Cells by EBIC and Cathodoluminescence.

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The space photovoltaic power systems for communication satellites requires solar cells with high power density. Communication satellite networks are being developed to operate in orbits in or near the proton radiation belts, which extend from approximately 2000 to 10,000 km (MEO : Medium Earth Orbit). The radiation damage produced at such orbits are equivalent to that of 1 MeV electron influence of 3×10^{15} electron/cm ^{2}. Hence, there is a need of radiation resistant, high-efficiency solar cells. $In_{0.5}Ga_{0.5}P$ solar cells which have a wide band gap of about 1.9 eV are appropriate for the top cell of high efficient dual - junction DJ - InGaP/GaAs cells. In this contribution we investigate the effects of 3MeV proton irradiation at fluences of 1×10^{14}proton/cm^2 on single - junction SJp^+ - n $In_{0.5}Ga_{0.5}P$ solar cells, that represents the top cell of the DJ one, by means of Electron-Beam-Induced-Current (EBIC) and Cathodoluminesence (CL). We demonstrate the potential of these techniques for optoelectronic and microelectronic devise failure analysis in terms of spatial distribution of diffusion length and non-radiative recombination centres.

For EBIC measurements, a p^+-n InGaP solar cell was mounted on an adapted holder of a JEOL - JSM820 scanning electron microscope in the planar configuration, i.e., with the incident electron beam perpendicularly to the epilayers. The EBIC current, I_{cc} , was measured using a head amplifier to low input impedance amplifier. The electron beam current I_b, was measured by a Faraday cup. I_{cc} and I_b are collected at different electron beam energies between 1-30KeV. The measured dependence of EBIC gain (I_{cc}/I_b) versus the electron beam energy, compared to that numerically simulated allows to estimate the spatial distribution of the minority carrier diffusion length. This technique is non-destructive, which is suitable to characterise operational semiconductor devices.

For EBIC quantitative analysis, our approach consists of firstly estimating the extent of electron-hole pair (E-h) generation by a Monte Carlo procedure. Secondly, the Poisson and the e-h current density continuity equations are resolved applying a self consistent iterative finite difference method.

The EBIC data shows that irradiation with 3 MeV protons with a fluence of 1×10^{14} proton/cm^2 produces some carrier removal and compensation effects highly localised at the top of the cell (~75nm - 100nm in depth). Hence, a non uniform defect distribution is expected to be induced by proton irradiation.

The CL measurements were made on a freshly cleaved {110} face perpendicular to the epilayers. From CL measurements, we obtain an uniform distribution of non-radiative recombination centres in bulk and a catastrophic suppression of the band-to-band luminescence 70 -75 μm in depth.

ELECTRON IRRADIATION AND THERMAL ANNEALING EFFECTS ON GaAs SOLAR CELLS

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ABSTRACT

This paper describes the effects of electron irradiation and subsequent thermal annealing on $Al_xGa_{1-x}As/GaAs$ heterojunction solar cells. The purpose of this work is to understand the operating performance of GaAs solar cells in space environment.

The $Al_xGa_{1-x}As/GaAs$ solar cells used in this experiment were fabricated by using a multi-wafers LPE technique. The structure of our cells is p^+-$Al_xGa_{1-x}As/p^+$-GaAs/n-GaAs/n^+-GaAs substrate, with the conversion efficiency up to 20.03% (AM0, 100mw/cm^2, 25°C). The n^+-substrate is doped by Sn with the concentration of $1x10^{18}cm^{-3}$. The n-buffer layer is doped by Sn, with the concentration of $2x10^{17}cm^{-3}$ and thickness of about 20μm. The p^+-$Al_xGa_{1-x}As$ window layer is Zn-doped, with the concentration $p=2x10^{18}cm^{-3}$, thickness of about 0.5μm and Al composition x = 0.8. The p-n junction is simultaneously formed in n-buffer layer due to Zn atoms diffusing during epitaxy growth process of the window layer, the average concentration of p^+-GaAs layer is $2x10^{18}cm^{-3}$, and the thickness is changed from 0.6 to 2.8μm, depending on the growth temperature. The contacts are formed by photolithography, vacuum evaporation and electroplating. The front contact is TiAu and the back contact is AuGeNi. The antireflection coating is an anodized film of $Al_xGa_{1-x}As$ layer, formed by electron-chemical method.

The electron irradiation experiments were performed in a Lineal Electron Accelerator, at 3 MeV energy with fluences from $1x10^{14}$ to $5x10^{15}$ e/cm^2. Two groups of samples were irradiated, one with a shallow junction depth of about 0.6 μm, the other with a deeper junction depth of about 2.8 μm. From the results of irradiation experiments it was seen that the $Al_xGa_{1-x}As/GaAs$ solar cells with a shallow junction have better radiation hardness than those with a deeper junction.

The effects of thermal annealing on the irradiated solar cells were also investigated. From the results of photovoltaic measurements prior to and after thermal annealing, we found that the low temperature annealing from 200 to 300°C is very efficient for recovery of the performances on irradiated GaAs solar cells. For instance, the performances of irradiated cells could be mostly recovered, even approach to their original values, after 260°C, 30 minutes annealing. This result is very useful for GaAs solar cells in space application.

DLTS measurements were carried out to determine the irradiation-induced damage centers in $Al_xGa_{1-x}As/GaAs$ solar cells. Four electron traps were recorded in irradiated samples, which are located below the conduction band at 0.24, 0.41, 0.51, and 0.59eV, respectively, and their densities were found to decrease with increasing annealing temperature. The results of DLTS could be used to explain the electron irradiation and thermal annealing effects on the irradiated GaAs solar cells.

Prof. X. B. Xiang is the auther for all correspondence

Structural Characterisation of InGaP/GaAs Heterojunction Bipolar Transistors.

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Heterojunction bipolar transistors (HBTs) based on epitaxial n-InGaP/p+GaAs/n-GaAs are very promising for high power microwave frequency applications. Successful device fabrication requires extensive structural characterisation for control of epitaxial substrates and subsequent processing. Here, we describe the techniques being applied in a study of the origins of long-term degradation in transistor gain observed in some devices after electrical stressing at elevated temperatures.

Substrate parameters which may affect long-term device performance include residual strain, defects and impurities. We describe an X-ray diffraction method for the sensitive determination of mismatch strain in the InGaP emitter and C-doped p+-GaAs base layers. Accurate values of InGaP composition and thickness are derived. We use secondary ion mass spectrometry (SIMS) to measure C dopant and H impurity depth profiles, and atomic force microscopy and X-ray topography to detect crystallographic defects. Substrates from two different sources are compared.

Focused ion beam (FIB) methods allow direct structural characterisation of specific completed devices, for correlation with process history on the one hand, and with measured electrical performance on the other. We firstly describe the use of FIB microscopy for direct sectioning and imaging of devises, and secondly for the preparation of transmission electron microscopy (TEM) specimens. In the latter case, a "lift off" process, requiring no pre-preparation of the device wafer, is demonstrated.

Session 3

Widebandgap Materials

Monday, 2.00 p.m – 4.00 p.m.

Chair : W. Jantz

III-NITRIDES FOR RED AND IR APPLICATIONS

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While the III-nitrides have received enormous attention in the last few years, most of the work has focused on the materials needed for fabrication of blue emitting photonic devices or high power/high temperature electronic devices. There are other applications, however, which may also benefit from the development of III-Nitrides. There is interest, for example, in developing efficient yellow and red nitride-based LEDs. This requires the growth of $In_xGa_{1-x}N$ with x varying from 0.5 - 1.0. Unfortunately, this range of compositions is quite difficult to grow with the characteristics needed for use in high performance devices. In this talk we will discuss the constraints placed on the synthesis of this material by the physical properties of InN, and our results obtained using gas source molecular beam epitaxy (GSMBE) and metalorganic MBE (MOMBE) for growth of InN. In particular the source of the high electron concentration normally obtrained in InN will be examined.

The second long wavelength application for III-Nitrides is fabrication of 1.54um emitters for use in fiber communication systems and optical interconnects. It has been shown that inclusion of rare earth elements such as Er into semiconductor or insulator materials can be used to produce emission at fairly precise wavelengths. This emission is due to internal transitions within the rare earth making the emitted wavelength relatively insensitive to the bandgap of the host material. However, though the wavelength is not affected, the intensity is strongly dependent on the nature of the host. Hosts with larger bandgaps and more ionic bonding tend to produce the best emission characteristics. Both criteria are present in the III-Nitride system. The second half of the talk will describe our work on Er doping of AlN and GaN using GSMBE, and the improvements in thermal stability that can be obtained using nitride hosts.

LARGE AREA GaN SUBSTRATES

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Bulk GaN would be the most promising substrate material for obtaining the higher quality of gomoepitaxial films. There is interest in producing large area bulk GaN substrates for group III nitride optoelectronic and electronic device applications. Success with traditional bulk crystal growth processes has been limited because of high decomposition pressure and the high melting temperature.

We report on the successful growth of large area bulk GaN single crystals using the rapid growth rates obtainable with hydride vapor phase epitaxy (HVPE). Seed crystals were grown by MOCVD in a low pressure horizontal cold-wall reactor on $LiGaO_2$ substrates. This film serves to protect the $LiGaO_2$ from attack by HCl. The key to obtaining high quality MOCVD GaN on $LiGaO_2$ is the initial surface nitridation step. It is believed that a surface reaction product is formed during nitridation that promotes recrystallization of the underlying $LiGaO_2$ and shows a lattice parameter very close to that of GaN. Furthermore, this reaction product serves as an efficient barrier for Li transport into the GaN. The surface of the MOCVD grown GaN was atomically flat (surface roughness R_g=0.036 nm) and the bulk microstructure was excellent as judged by TEM and HRXRD analysis. The $LiGaO_2$ substrate with the MOCVD grown GaN capping layer was transferred to the HVPE system. The deposition was conducted in the temperature range 850 to 950 °C and at atmospheric pressure with a growth rate 50 to 70 μm/hr. The oxide substrate was subsequently removed by wet chemical etching, leaving large area free-standing wafers of GaN. At certain growth conditions the GaN peeled off the $LiGaO_2$ substrate leaving a free-standing film of GaN. LRXRD spectra revealed the GaN (0002) and (0004) diffraction peaks. Growth studies and film characterization results of thick GaN films are presented. The surface morphology was determined by AFM, the structural quality was analyzed by TEM and XRD, while the composition was investigated by AES, SNMS, SIMS and ESCA.

STRUCTURAL CHARACTERISATION OF InGaN/GaN LAYERS BY TRANSMISSION ELECTRON MICROSCOPY

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Transmission electron microscopy is used to examine the microstructure of high quality hexagonal InGaN/GaN layers grown by MOCVD. It is shown that a combination of imaging and convergent beam diffraction techniques gives information on the types of threading dislocation present, and on the structure of nanopipes, inversion domains and inversion domain boundaries. Recent results which throw new light on the nanopipe formation mechanism are also reported.

We also present preliminary work in which electron holography has been used to investigate piezoelectric fields generated across strained InGaN quantum wells.

POINT DEFECT CHARACTERIZATION OF GaN AND ZnO

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The electrical and optical properties of wide-gap semiconductors, such as GaN and ZnO, are often controlled, or at least strongly influenced, by point defects. For example, a longstanding controversy exists in GaN over whether the dominant residual donor in that material is the N vacancy V_N or some impurity, such as O_N or Si_{Ga}. The same is true in ZnO, except that the donor there is thought to be either the O vacancy V_O or the Zn interstitial Zn_I. Furthermore, a very recent report on the failure mechanisms in GaN blue light-emitting diodes suggests that the major degradation effect is the recombination-enhanced creation of V_N defects which compensate acceptors in the p-region. Finally, theoretical studies, supported by positron annihilation experiments, conjecture that the Ga vacancy V_{Ga} is the dominant compensation species in as-grown, n-type GaN. Thus, point defects are very important in GaN and ZnO.

Analogous to the use of implantation and diffusion methods to inject impurities, we can use high-energy electron irradiation to inject defects (no other method is well controlled). We have irradiated epitaxial GaN and bulk ZnO with 0.7-2.0 MeV electrons and studied the optical and electrical effects with photoluminescence (PL), temperature-dependent Hall-effect (TDH), and deep-level transient spectroscopy (DLTS) measurements. The TDH measurements in GaN are quite definitive, and show that N Frenkel (V_N-N_I) pairs are formed, and that V_N, as expected, is a shallow donor and that N_I is, surprisingly, an acceptor. However, by comparing donor energies in various samples, it can be stated that V_N is not the *dominant* donor in the best (highest-mobility) layers being grown nowadays. The DLTS experiments find an electron trap with an activation energy of about 0.18 eV, which is most likely also related to V_N, although the activation energy is 0.11 eV larger than that found by the TDH technique. The difference is probably due to a capture barrier, arising because the *empty* V_N level lies above the conduction-band edge. The PL spectra show an irradiation-induced band at about 0.93 eV, which one research group tentatively attributes to a Ga_I complex. The electron irradiation also introduces nonradiative centers, as evidenced by the overall drop in PL intensity.

In ZnO, the defect production rate is sample dependent, which is probably because some of the atoms are near dislocations and are more weakly bonded. In the best samples, the defect production rate is very low, in some cases below 0.02 cm^{-1} at 2 MeV. In fact, even the "worst" samples show rates less than 0.1 cm^{-1}, which is an order of magnitude below rates found in GaN, GaAs, and Si. Thus, ZnO is very "rad-hard" and may be an excellent candidate for optoelectronic devices in space applications. In this regard, we may note that the bulk ZnO examined by us has extremely sharp PL lines ($\approx$ 0.1 meV FWHM), and much brighter UV emission than that seen in even the best GaN layers that we have studied. Part of the reason for that is likely the large lattice and thermal mismatches between GaN and Al_2O_3, the most common substrate. In fact, a GaN layer on a ZnO substrate would be a much more compatible combination, and such a technology is being pursued by several groups. In the end, each material will probably have commercial optoelectronic applications, but optimization will be difficult without a thorough understanding of the point defects in each system.

Optical Mapping of the net Donor Concentration in n-type SiC

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Electrical homogeneity is a predominant requirement to technical semiconductor material. It strongly affects the yield in the production of many electronic devices. While high degrees of homogeneity in dopant concentrations have been achieved in standard materials like Si, GaAs and InP, the situation is still strongly unsatisfactory for SiC, material with considerable promise for high power and high temperature electronics as well as substrate material for blue LEDs. So, for further material development and quality control, a method would be highly desirable to check the homogeneity of carrier concentration in SiC wafers in a reliable, quick and nondestructive way. Our investigations reveal that such a method is provided by optical mapping of SiC wafers based on the fact that the free carriers (electrons) as well as the occupied donors absorb light in the visible spectral range (around 410nm as well as 600nm in 6H-material, around 470nm in 4H-material). The usability of free carrier absorption for investigation of carrier homogeneity is demonstrated by comparison of optical and Hall measurements in a number of n-type samples of 4H- and 6H-polytype grown in our institute. The optical absorption coefficient in the respective spectral regions turns out to be proportional to the net dopant concentration $N_D - N_A$ at room temperature. The absolute values of the underlying absorption cross sections are subject to uncertainties related to the interpretation of the Hall data which will be discussed.
The method is applied to wafers of 6H- and 4H-polytype as well as to investigations of dopant concentrations along the growth direction. Characteristic features related, e.g. to facette growth, will be discussed.

Characterization of deep level trap centers in 6H-SiC pn junction diodes.

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Abstract:

We have performed deep level transient spectroscopy (D.L.T.S) measurements on silicon carbide (6H-SiC) $n^+p^-p^+$ junction diodes in order to compare the electrical properties and quality of epitaxial layers in the implanted and the epitaxial emitter diodes, where the p^-p^+ layers are the same ones. Four hole trap centers have been observed on the implanted emitter diodes. Their thermal activation energy are respectively 0.49 eV, 0.6 eV, 0.7 eV and 0.87 eV, referred to the valence band. The last three trap centers are also observed on the epitaxial emitter diodes. The origin of deep levels with Ea = 0.7 eV and 0.87 eV is still under investigation. The thermal activation energy and capture cross section (0.6 eV, 4.3×10^{-15} cm^2) is in good agreement with values reported for the boron-related D-center. The trap center with E_a = 0.49 eV is associated to the ion-implantation process of the n^+ layer.

Double deep level transient spectroscopy measurements (DDLTS) have been performed to accurately profile this last defect through the depletion region. Its trap concentration N_T as a function of the depletion region width indicates that this defect is located near the n^+/p^- junction.

Keywords: SiC, p-n junction diode, c-DLTS, deep level, hole trap center, capture cross section, DDLTS.

Session 4

Characterisation and Monitoring I

Tuesday, 8.30 a.m – 10.30 a.m.

Chair : S. Krawczyk

IN-LINE AND IN-SITU MONITORING AND CONTROL OF SEMICONDUCTOR ALLOY DEVICE STRUCTURES USING SPECTROSCOPIC ELLIPSOMETRY

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Spectroscopic ellipsometry (SE) is becoming the preferred technique for non-destructive in-line or real-time in-situ process monitoring and control. SE can be used in two modes: (i) in real time to monitor the change in the vertical dimension during deposition or etching at a single point (usually the wafer centre), and (ii) after deposition to map the uniformity of a multilayer structure in the lateral dimension. Both modes can be used for process control--(i) for real-time control or endpointing, (ii) for conventional in-line control. Applications for real-time control are still under development but SE-based instruments are now mature enough to be used for automatic in-line process monitoring of product wafers in cleanroom conditions. Post-growth information can be obtained rapidly and non-destructively on layer thickness, alloy composition, crystallinity, strain and surface roughness on both monitor and patterned wafers. Real-time SE (RTSE) used in situ can monitor and control growth rate, alloy composition, interface sharpness and wafer temperature. Newly-developed photo-modulation techniques such as photoreflectance and photo-SE (PSE) are complementary to SE in that they can provide electric field and critical point information with reduced sensitivity to multilayer interferences. Application of the techniques will be discussed for real-time monitoring/control and ex-situ mapping of the strained Si/SiGe system. This alloy system can be used as a generic example and similar applications in III-V systems wil be discussed. Novel algorithms based on neural networks have been developed for rapid analysis of the real-time data. Extensive cross-correlation with direct techniques such as SIMS, XRD, XTEM, AFM, RBS has been performed to validate the indirect SE measurements.

OPTIMISATION OF EXPERIMENTAL CONDITIONS FOR VARIABLE ANGLE SPECTROSCOPIC ELLIPSOMETRY ANALYSIS. APPLICATION TO GaAs/AlGaAs QUANTUM WELLS CHARACTERISATION.

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Spectroscopic Ellipsometry (SE) proved to be a non destructive tool, suitable to the study of multilayered semiconductor heterostructures. As regards thin films of III-V alloys, the sample characterisation involves the thickness determination and the dielectric functions of the material. The standard ellipsometric angles Ψ and Δ are related to ρ by : $\rho = \tan\Psi e^{i\Delta}$ where ρ is the complex ratio between the reflection coefficients of light polarised parallel (r_p) and perpendicular (r_s) to the plane of incidence.

The SE data are analysed using a program which calculates $\tan\Psi$ and $\cos\Delta$ for an assumed model of the sample, then minimises a mean-square type difference χ^2 between measured and calculated values of $\tan\Psi$ and $\cos\Delta$ by varying model parameters (q_i, i=1...P). The goodness of the fit is measured by a figure of merit (*FOM*) : $FOM = \chi^2 / (\mathrm{N} - \mathrm{P} - 1)$. N is the total number of data points. The elements D_{ij} of the inverse matrix D of the curvature matrix H ($H_{i,j} = \partial^2 \chi^2 / \partial q_i \partial q_j$) are related to the error limit on the parameters and to correlations between parameters [1].

In order to obtain correct estimates, the number of independently obtained data used should be equal to or greater than the number of unknown parameters. Over the last decade, variable angle of incidence spectroscopic ellipsometry has proved to be suitable technique for increasing the number of independent observations. **Such studies can be significantly improved by choosing carefully the set of angles of incidence before performing the experiments.**

To our knowledge, no systematic research of the best set of angles of incidence, taking into account the sensitivities as well as the problem of correlation between parameters and between data collected at several angles of incidence has been published yet. As most of authors give the confidence limit of fitted parameter q_i in term of $\sqrt{D_{ii}}$ [1], we propose to choose a set of angles of incidence which minimises $\sqrt{D_{ii}}/q_i$ for each parameter q_i.

A MBE (Molecular Beam Epitaxy) grown GaAs /AlGaAs quantum well structure has been investigated using the above experimental procedure. Partial results are given in the table below. The dielectric functions for $Al_x Ga_{(1-x)}As$ for x=0 to x=0.8 come from reference [2]. The model of the sample is derived from growth specifications (composition x_i and thickness d_i are targeted values). For a $\phi = 73°$ angle of incidence, the expected theoretical uncertainty limits on the parameters ($1.65\sqrt{D_{ii}}$) are listed in the first column of the table, they are larger than those expected for the optimum couple of angle of incidence (75°,76°) (2nd column). In the last column, the values of parameters obtained from the experimental data collected at 75° and 76° are reported. The standard deviations are $\sqrt{FOM}\sqrt{D_{ii}}$ according to reference [1] in order to take into account the agreement between the multilayers model and the actual structure of the sample too. Even if a study of the composition profiles at the interface GaAs/AlGaAs (in progress) is expected to improve the quality of the fit, this example demonstrate the interest of a reasoned procedure for the choice of the angles of incidence in order to make the best possible use of a sample.

Parameter	ϕ=73° Theoretical	ϕ=75° and 76° Theoretical	ϕ=75° and 76° Experimental
d_1	30.00 ± 0.05 Å	30.00 ± 0.03 Å	32.1 ± 0.2 Å
d_2	170.0 ± 0.5 Å	170 ± 0.08 Å	163 ± 2 Å
d_3	2000 ± 3 Å	2000.0 ± 0.3 Å	2034 ± 9 Å
x_3	30.0 ± 0.1 %	30.00 ± 0.04 %	29.3 ± 0.6 %
d_4	96 ± 1 Å	96.0 ± 0.2 Å	109 ± 7 Å
d_5	2000 ± 3 Å	2000.0 ± 0.3 Å	2007 ± 15 Å
x_5	30.0 ± 0.4 %	30.00 ± 0.06 %	29 ± 2 %

Oxide of GaAs, d_1
GaAs, d_2
$Al_{x3}Ga_{(1-x3)}As$, d_3
GaAs, d_4
$Al_{x5}Ga_{(1-x5)}As$, d_5
GaAs

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REAL-TIME STRAIN MONITORING IN THIN FILM GROWTH: CUBIC BORON NITRIDE ON Si (100)

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The zinc-blende nitrides (c-BN, cubic GaN, ...) form an important emerging class of wide-bandgap semiconductors of interest for high-power optoelectronic devices operating under rugged conditions. An ongoing challenge towards fabrication of devices from such materials is to find appropriate substrates and buffer layers that will promote epitaxial growth while minimizing stress buildup. In this presentation we describe a novel approach to this issue, recognizing the prevalence of *polymorphic structures* in these nitrides. The wurtzitic and hexagonal (turbostratic) forms are particularly interesting as strain-relieving buffer-layers for the growth of cubic phases of the same III-N compound. We term such buffer layers, "**self-compliant**". Drawing on the example of cubic boron nitride (c-BN), our studies [1] demonstrate the use of hexagonal buffer layers of BN to relieve stress build-up and to promote oriented growth of c-BN on Si (100) substrates. *In-situ* measurements of film strain will be presented illustrating a new technique [2] in which an array of laser beams reflected off the substrate surface is monitored in-real time by a CCD area detector. The measurements show that a dramatic reduction in stress can be achieved by use of self-compliant buffer layers, and by optimization of deposition parameters such as substrate temperature and incident ion (N^+) energy, leading to improved adhesion, increased growth rates, and a well-oriented mosaic structure.

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Work supported by the ONR Nitride Program under Grants N00014-91-J-1398 and N00014-94-J-0763

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The Use of In-Situ Interferometry for MCVD Process Control.

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This paper reports on the technique of single wavelength laser interferometry for remote monitoring of the thin film growth of semiconductors by Metal-Organic Chemical Vapour Deposition (MOCVD). The predictable nature of an interferogram during film growth indicates how single wavelength interferometry might be used as a tool for process control of a growth process. By on-line fitting of factors governing the complex refractive index of a growing layer, the quality of epitaxial growth can be constantly monitored and early identification of a degradation in film growth identified. For example, sub-bandgap 633nm (He/Ne) radiation was used to monitor the pyrolytic and photo-assisted growth several films of ZnTe on GaAs. Under pyrolytic conditions fitting of the effective extinction coefficient (k_{eff}) at each peak and trough in the interferogram gave consistently low values (<0.02), as would be expected at this probe wavelength for good quality growth. However for the growth of similar layers under photo-assisted conditions, fitting of the effective extinction coefficient is seen to be anomalous, indicating that different growth mechanisms occur under photo-assisted conditions compared to strictly pyrolytic conditions.

We have developed a virtual interface approach [1,2] for the mathematical treatment of a dielectric stack for the real-time fitting of complex reflectance interferograms from multilayers. In this approach the individual complex refractive index values for each layer within a stack are ignored and the entire underlying structure is described by a single "virtual" complex refractive index. Using this model, interferograms for VCSEL structures have been theoretically generated and are in excellent agreement with the interferograms recorded by Killen *et al* [2].

In some heteroepitaxial processes, growth polarity has to be selected, for example the growth of a CdTe buffer layer on Sapphire for the production of mid-wave focal plane arrays requires that the growth be B-face. The 3-D faceted nature of this growth process results in a decrease in the overall reflected intensity as the layers develop. This rate of decay is seen to be dependant on the orientation of growth (A-face vs.B-face) with the more rapid decay occurring with B-face growth. This distinction in the rate of decay of the average reflectance with orientation of growth is apparent within the first micron of material deposited, thus layer interferometry is an excellent metric for early recognition of the correct orientation of growth in this process.

Finally, as an example of the use of laser interferometry for process control on an industrial reactor, reflectance data will be presented from the growth of a CdTe buffer layer on Sapphire on the Boeing EOC reactor at Anaheim, California, USA. These data demonstrate the reproducible nature of the reflectance "signature" for this growth process.

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LUMINESCENCE IMAGING - A WELL ESTABLISHED TECHNIQUE TO STUDY MATERIAL- AND DEVICE-RELATED PROBLEMS

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Performance, yield and reliability of micro- and optoelectronic devices are crucially dependent on the quality of substrates and epitaxial layers, determined by the lateral homogeneity of various material parameters and by a low defect density. The assessment of these properties requires techniques that are capable of measuring the full wafer area as well as microscopic defect structures. Optical imaging combines fast, nondestructive data acquisition with high lateral resolution. Two complementary imaging techniques - photoluminescence topography (PLT) and photoluminescence microscopy (PLM), introduced about ten years ago - have continuously been improved and are now well established workhorses of both routine and in-depth material and process analysis.

The present technical status of luminescence imaging will briefly be reviewed. State-of-the-art PLT systems feature spectrally selective excitation with tunable lasers, spectrally selective imaging using either rapid monochromator scanning or recording with a diode array detector, measurement at low temperature down to 2K and beam expanding techniques to achieve high spatial resolution. High performance PLM systems are equipped with a sensitive digital camera, cryostatic cooling and interference filter wavelength selection.

Typical examples of material and process analysis with PLT will be reported, including the assessment of epitaxial layer homogeneity and interface quality, routine substrate homogeneity evaluation as well as detailed investigations to determine the mesoscopic distribution of acceptors in semi-insulating GaAs. Ways to determine lifetime and dopant variations across a wafer will be discussed. To demonstrate the merits of PLM, luminescence images of substrate and growth induced defect structures will be presented, e.g. allowing a quick and precise determination of the onset of lattice relaxation of strained layers. Recent PLM investigations of the failure mechanisms responsible for performance degradation of laser diodes will be described.

"AN OPTICAL STUDY OF THE PROPERTIES OF $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ EPITAXIAL LAYERS WITH VARYING COMPOSITION AND GaAs SUBSTRATE ORIENTATION"

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The $(AlGa)_{0.51}In_{0.49}P$ material system is extremely important due to its use in visible laser (620-680nm) and HB-LED (570-630nm) structures e.g. for DVD optical data storage and LED display and lamp applications. All these applications rely on high brightness and efficiency of the fundamental semiconductor materials in the final device. Assessment and optimisation of the optical efficiency of $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ materials is therefore crucial to the production of high efficiency optical devices.

An extensive set of experiments have been performed to study the properties of $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ epitaxial layers and heterostructures. Samples comprised p-$Al_{0.51}In_{0.49}P$/p-$(Al_xGa_{1-x})_{0.51}In_{0.49}P$/p-$Al_{0.51}In_{0.49}P$ double heterostructures (DH) suitably designed for optical measurements. All samples in this study were grown by low pressure MOVPE in a multi-wafer reactor. Three different substrate types were included, in each growth run, with varying misorientation from the (001) crystallographic direction. The substrates had misorientations of 2° towards <110>, 10° towards <111A> and 15° towards <111A>. The $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ epitaxial layers were evaluated using double crystal X-ray diffraction measurements to ensure lattice-matching to the GaAs substrate. The net acceptor concentration in each layer was measured using the Polaron C-V profiling technique.

Optical studies were performed using photoluminescence (PL) at 300°K and 4.2°K, and photoluminescence excitation spectroscopy (PLE) at 4.2°K, to evaluate the radiative efficiency and band-structure of $Al_{0.51}In_{0.49}P/(Al_xGa_{1-x})_{0.51}In_{0.49}P/Al_{0.51}In_{0.49}P$ double heterostructures. The optical properties of $(Al_xGa_{1-x})_{0.51}In_{0.49}P$, grown on 10° substrate type, were investigated as a function of x, the Al mole-fraction in the solid from x=0 to 0.46. An estimate of the room temperature band-gap dependence on x was determined from PL and PLE, to be ***Eg=1.9+0.7x***.

The 300°K PL intensity was also measured as a function of x for the same samples and the other substrate orientations. A factor of ≈10 decrease in peak PL intensity was observed, for samples grown on 10° and 15° misorientated substrates as the emission wavelength changed from around 650 nm to around 560 nm. In comparison, the 2° misorientated substrate showed a much larger decrease in PL intensity of ≈80 over the same compositional range. The PL emission wavelength for the 2° substrate showed an increase of ≈ 11 nm compared to the 10° and 15° substrates from the same growth run. This shift of ≈ 11 nm was consistent over the whole compositional range studied and is explained by differences in the degree of ordering of the AlGaInP alloy as a function of substrate orientation[1].

The decrease in optical efficiency with increasing x is thought to be due either to the increasing concentration of non-radiative centres or to the approach of the Γ-X conduction band crossover, both of which are caused by the increasing concentration of Al in the solid. In order to distinguish between these two possible mechanisms, hydrostatic pressure measurements were performed. Hydrostatic pressure allows the relative positions of the conduction band minima to be altered in the same sample without any change in material composition. PL measurements were conducted on an $Al_{0.51}In_{0.49}P/Ga_{0.51}In_{0.49}P/Al_{0.51}In_{0.49}P$ DH sample in a miniature diamond anvil cell[2]. As the pressure was applied so the emission wavelength decreased, due to the increase of the Γ conduction band energy. The PL intensity for a given shift in wavelength was compared to the PL intensity observed for a similar shift obtained by the addition of Al in the active region of the DH. A much smaller decrease in PL intensity was observed using hydrostatic pressure, for a given change in band-gap, implying the dominance of non-radiative centres associated with increasing Al on the optical efficiency of $(Al_xGa_{1-x})_{0.51}In_{0.49}P$.

This work was carried out under the DTI/EPSRC Photonics LINK project "GLLAD".

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Session 5

Characterisation and Monitoring II

Tuesday, 2.00 p.m – 3.30 p.m

Chair : R. Wallis

Contactless Electroreflectance Characterisation of GaInP/GaAs heterojunction Bipolar Transistor Structures

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We have used contactless electroreflectance (CER) to characterise several GaInP/GaAs (001) heterojunction bipolar transistor structures fabricated by metallorganic chemical vapour deposition (MOCVD) and chemical beam epitaxy (CBE). The ordering parameters (h) deduced from the dependence of the GaInP emitter spectrum on the polarisation {[110] and [110]} of the incident radiation were consistent with TEM measurements of ordering, obtained from selected area diffraction patterns. The quantity h can be extracted either from the band gap reduction or from the measured anistropy in the band gap (between polarisation of the incident light along the [110] or [110] directions). The equivalence of the values obtained by these two methods allowed us to conclude that the GaInP was lattice matched to the GaAs.

From the observed Franz-Keldysh oscillations we have evaluated the electric fields in the collector/base and emitter/base regions. These fields are in good agreement with a calculation based on a comprehensive, self-consistent model, including the photovoltaic effect. Along with further measurements that were taken at varying light intensities, these data permitted us to extract doping levels and carrier lifetimes in both the emitter and the collector.

From an application standpoint, CER and its companion technique, photoreflectance, are shown to be powerful non-destructive, non-contact techniques that can be used on production wafers to monitor doping, composition, lattice matching, lattice ordering, and both minority and majority carrier lifetimes.

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InGaP/GaAs BASED HETEROJUNCTION BIPOLAR TRANSISTOR CHARACTERISATION USING NON-CONTACT ELECTRO-OPTIC DIAGNOSTIC TOOLS

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Hetero-junction bipolar transistors (HBT) are well established devices for a wide range of microwave and power applications as well as for various digital and non-linear applications e.g. low phase noise oscillators. The conventional GaAlAs/GaAs HBT has been used most widely heretofore, however as suggested by Kroemer[1], HBT's based upon the InGaP/GaAs material system demonstrate several fundamental advantages over that of AlGaAs/GaAs, namely : improved carrier injection into the base because of the higher InGaP band gap, a more favourable conduction band alignment at the heterojunction, the absence of DX centres and a lower surface recombination velocity as well as processing attributes such as lower reactivity of InGaP with oxygen (with respect to AlGaAs) and also better etch selectivity between InGaP and GaAs.

The current practise of building test structures and obtaining dopant concentrations and device characteristics, such as current gain and breakdown voltage is a costly and time consuming activity. These tests of course, are necessary in order to assess the quality and suitability of the material for device processing. Clearly, therefore, the application of non-destructive, non-contact i.e. non-intrusive characterisation or monitoring tools could have a very significant impact upon the cost and yield of devices. Such diagnostic tools should be capable of dealing with the complex nature of semiconductor growth i.e. multi-layer, binary and ternary alloys, compositional grading and other features representative of advanced HBT technology. Optical probes appear ideally suited to the task however, proving to be sensitive to material properties [2] as well as various processing steps which are related to actual device parameters and performance[3].

In this work we report the application of several optical spectroscopic techniques such as Photoreflectance (PR), Ellipsometry, Photoluminescence and Raman backscattering for characterising InGaP/GaAs multi-layer HBT material. The results reveal important information regarding the quality of the different InGaP and GaAs layers for both the Emitter, Base, Collector and surface cap regions. As well as valuable monitoring of both the Collector and Emitter dopant concentrations, PR analysis of the InGaP band structure, in particular, reveals clear evidence of some interfacial mixing at the InGaP/GaAs heterojunction. This layer proves to have adverse consequences for the current gain characteristics of the resultant HBT device, determined by measurements of the DC characteristics i.e. common emitter current gains. Evidence of the existence of this intermixing layer is further supported by the ellipsometric data revealing both layer composition and thickness while stress analysis of the surface GaAs layers, from the Raman data, also suggest some sensitivity to the intermixed layer.

PR spectral information is correlated with PL results while extracted interfacial electric field data are also supported by device finite-element (ANSYS) modelling of the space distributed values e.g. potentials including device current(capacitance)/voltage characteristics. The results are finally correlated with structural information from Secondary-Ion-Mass-Spectroscopy and Transmission-Electron-Microscopy of the HBT wafer samples.

In summary this paper demonstrates the crucial importance of non-destructive - and rapid - techniques for evaluation and control of compound semiconductor materials for HBT technology.

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INDUSTRIAL CHARACTERISATION OF III - V EPILAYERS

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Abstract

As the production volume of III - V semiconductor epi - layer wafers has increased over the last ten years the demands placed on the assessment of these wafers has also increased. There is still a heavy reliance placed on post growth wafer characterisation, as opposed to in-situ characterisation within the reactor cell to guarantee the quality of a particular wafer product.

At Epitaxial Products International Ltd. (EPI), over three hundred measurements are carried out every 24 hours, 7 days of the week. These measurements are essential in the industrial manufacturing process and serve to test precursor quality, reactor integrity, product specification compliance and to maintain production control. Measurement quality is maintained through the use of documented measurement procedures, calibration, repeatability & reproducibility studies and control charts.

It is the adequacy of the measurement gauge that determines the measurement techniques applicability to process control. Once repeatability and reproducibility studies have been carried out the measurement gauge can be determined. Ideally the measurement gauge capability needs to be one tenth of the specification width for good process and quality control, although a measurement gauge of one third of the specification width may be considered acceptable. If the gauge is not considered to be adequate then either the number of measurements made has to be increased to improve confidence levels or a gauge improvement project has to be undertaken which may in turn lead to an alternative technique being employed.

This paper describes the characterisation facility at EPI and discusses some of the issues relating to calibration and measurement gauges. Measurement gauge data is presented for some of the main assessment techniques.

Finally, there is a description of a what a future characterisation facility might look like. The features of the facility include a characterisation cluster of tools which have built in calibration and control diagnostics and wafer handling capability. The cluster is designed to provide rapid feedback of surface morphology data and wafer mapped data of composition, lattice mismatch and layer thickness.

Session 6

Materials, Processing and Growth Issues

Wednesday, 8.30 a.m – 10.30 a.m.

Chair : C. Frigeri

The Upper Limits of Useful N and P-Type Doping of GaAs and AlAs

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Highly doped n-type GaAs:Si is required for low resistance contacts and high p-type doping of GaAs:C and AlAs:C is required for HBTs and DBRs respectively.

The incorporation of Ga vacancies (electron traps) limits n to $\sim 1.5 \times 10^{19}$ cm^{-3} in MBE GaAs:Si grown at $\sim 400^0C$. V_{Ga} defects form second neighbour pairs with Si_{Ga} donors to produce Si-X and Si-Y defects observed by infrared (IR) vibrational absorption. The assignment of Si-X has resulted from recent studies of single isotope ^{69}GaAs:Si layers [1]. Post-growth anneals at temperatures above 400^0C reduce the initial value of n since more vacancies are generated.

GaAs [2] or AlAs[3] can be doped with carbon to give $[C_{As}]$ greater than 10^{20} cm^{-3}. MOCVD growth introduces hydrogen and H-C_{As} pairs that are also detected by IR absorption. Anneals above $T \sim 550^0C$ remove the hydrogen but p drops (to $\sim 10^{19}$ cm^{-3} in GaAs) due to the formation of C-C split interstitial pairs (Raman active, hole traps). These centres are detected in some as-grown, as well as in annealed AlAs samples. It is implied that C_{As} acceptors must jump into interstitial sites and then diffuse to form the pairs. The fate of the resulting vacancy is not known. The maximum useful value of p in GaAs is $\sim 10^{19}$ cm^{-3}.

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Non-annealed ohmic contacts to p-GaSb grown by molecular beam epitaxy

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Ohmic contacts to p-GaSb have recently attracted some interest due to the potential of the antimonide system (GaSb/AlSb/InAs) for microwave and optoelectronic devices. We show in this study that neither the use of mostly volatile dopants (zinc or beryllium), neither gold based contacts, nor annealing are necessary requirements for excellent ohmic contacts to p-GaSb. Therefore, our focus lies on the application of refractory metals and on the omission of the annealing step. The latter has the advantage that diffusion processes are minimized and that the device fabrication steps can be more flexibly arranged. Since the annealing step maintains a dominant position in a fabrication process, it would determine the sequence of the steps. Stability of the ohmic contacts was investigated for heat treatments up to 250 °C. Some metal-GaSb interfaces were studied by cross-sectional transmission electron microscopy (XTEM).

The ohmic contacts were fabricated on p-GaSb layers grown by molecular beam epitaxy. Van der Pauw measurements gave a doping level of 6.2×10^{18} cm^{-3} and a hole mobility of 273 cm^2/Vs at room temperature. Transmission line method measurements were applied for determining the specific contact resistivity. A thickness of 30 nm of each refractory metal (Pd, Pt, Ti, Ni) was e-beam evaporated whereas 80 nm thick gold layers were thermally evaporated from a tungsten boat. The sample preparation of the XTEM studies demanded cooling during the ion etching in order to avoid preparation induced diffusion.

The non-annealed ohmic contacts using refractory metals led all to excellent specific contact resistivities. They were superior as compared to simple gold contacts. The Ti/Au contacts gave values between 2.58×10^{-7} Ωcm^2 and 2.8×10^{-5} Ωcm^2. The large spread is attributed to interface reactions between Ti and GaSb. Annealing did not change the contact resistivity which is in line with the results reported for the Ti/Pt/Au-contact [1, 2]. We have inferred specific contact resistivities between 4.14×10^{-6} Ωcm^2 and 5.88×10^{-6} Ωcm^2 by measuring the as-deposited Pt/Au contacts. Annealing at 200 °C for 1 min did improve the contact to $\rho_C = 1.71\times10^{-6}$ Ωcm^2. The Pd/Au ohmic contacts showed the best electrical results for the as-deposited condition: ρ_C varied between 2.88×10^{-7} Ωcm^2 and 3×10^{-6}Ωcm^2. Annealing did not improve these values. The good results are supported by the XTEM image of the Pd-GaSb after evaporation. A homogeneous interface reaction is apparent indicating that Pd possibly disperses the native oxides of GaSb (Fig. 1). We determined a specific contact resistivity of $\rho_C = 1\times10^{-5}$ Ωcm^2 for the non-annealed Ni/Au contacts. Annealing did not improve the ohmic contact. The gold contact exhibited the worst electrical results in the as-deposited state. We measured ρ_C between 2.7×10^{-5} Ωcm^2 and 1.9×10^{-4} Ωcm^2. Rapid thermal annealing at 250 °C for 1 min led to a specific contact resistivity of 1.35×10^{-5} Ωcm^2.

The Pd/Au, the Ti/Au and the Pt/Au contact showed the best electrical results whereas the Ni/Au and the Au contact were considerable worse. Non-annealed contacts are preferable as compared with annealed contacts due their excellent electrical results and their other advantages mentioned above.

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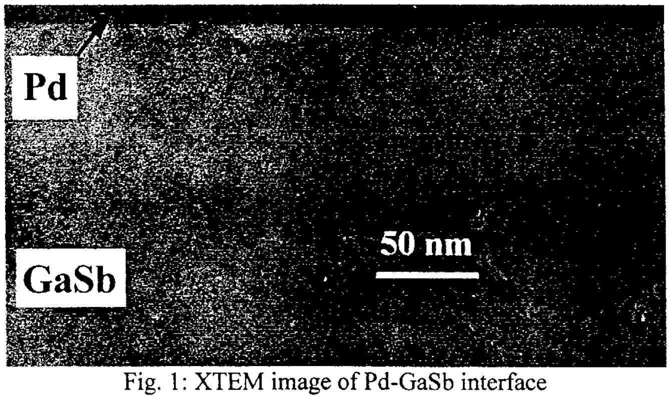

Fig. 1: XTEM image of Pd-GaSb interface

EXMATEC '98, 22-24 June 1998, Cardiff, UK.

Hydrogenation of buried passive sections in photonic circuits : A tool to improve propagation losses at ~1.56 μm

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ABSTRACT

Depending on the functionality of photonic circuits operating at ~1.56 μm, high propagation losses in the passive sections can be a severe limitation to their optimal performances. We address here the specific case of photonic integrated circuits (PICs) on InP in which the active (laser, amplifier, modulator, etc.,) and passive (straight guides or curved guides, Y-joints, intersections, etc.,) sections reside juxtaposed on the same chip surface. The **active guides** are always grown sandwiched between heavily n^+ and p^+ doped InP cladding layers, while such doped cladding layers on either side of the **passive guides** are a source of propagation losses through absorption by free carriers. Remembering that the absorption by free holes is far superior to that by electrons (at least 7 to 8 times), the trade off in the choice of integration technology can be summed up as follows. ***A single re-growth sequence for the upper p^+-InP cladding and contact layers, or repeated selective etchings followed by at least two separate re-growths, -doped layers on active sections and undoped layers on passive sections-***. In this regard, as will be shown here, the hydrogenation offers an attractive alternative solution. When performed spatially localized on the passive sections of completed photonic circuits, hydrogenation comforts the choice of single re-growth sequence with doped layers by **deactivating the Zn acceptors** in the upper p^+-InP cladding layer and reducing there by significantly the propagation losses in buried passive sections

We first discuss briefly the free carrier absorption mechanisms to show how prominent is the contribution of free holes in the upper p+-InP cladding layer to the propagation losses at 1.56 μm in the InGaAsP (λ_{gap} ~1.3 μm) guiding layer underneath. Later on, we present the relevant data on the optical properties of hydrogenated InGaAsP/InP buried waveguide test structures to specify the benefits of hydrogen passivation by exposure to deuterium plasma. Finally, the propagation losses measured at 1.56 μm in the waveguides before and after hydrogenation will be presented to demonstrate the efficiency of hydrogenation to bring down the losses. For example, depending on the structure drops in losses as high as 25 to 40 dB/cm have been measured. The lowest loss values achieved hither to, around ~5 dB/cm, are totally compatible with the development of complex photonic circuits [1]. This is demonstrated from a recent example of the realization of a distributed feed back (DFB) laser array monolithically integrated on InP with a 4 $\rightarrow$ 1 hydrogenated passive coupler [2].

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HIGHER YIELD OF 1.55 μm DFB LASERS THROUGH MOVPE GROWTH UNDER N_2 ATMOSPHERE WITH EXCELLENT HOMOGENEITY

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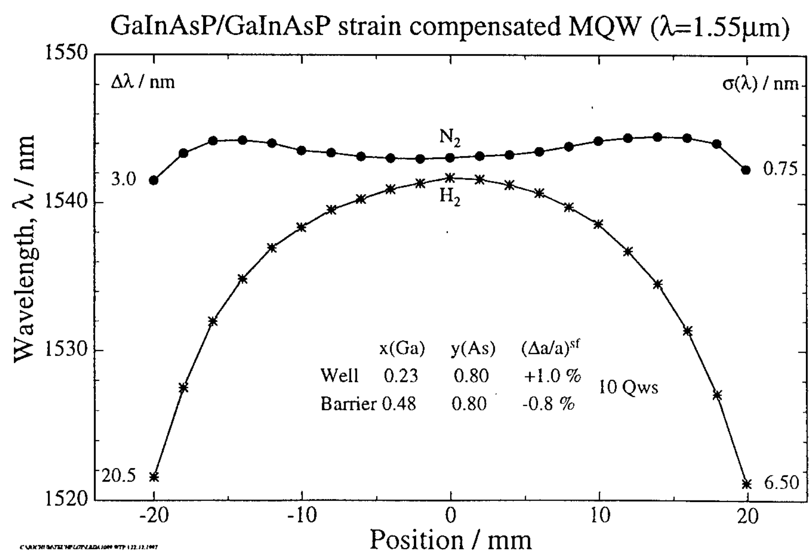
An essential condition for high device production yield is a good lateral homogeneity of the epitaxial structure. Especially, for 1.55 μm distributed feedback (DFB) lasers and laser arrays, which we manufacture for high-density wavelength division multiplexing (DWDM) applications, excellent emission wavelength uniformity over the wafer is indispensible. The problem is made complicate by the existence of two group-V elements in InGaAsP.
Growth was performed in a horizontal reactor (AIX200, Aixtron Corp.) with substrate rotation and IR heating using standard precursors at T=655°C and p_R=50 mbar. In this type of reactor geometry the inhomogeneity is mainly caused by side-wall reactions. In order to improve the homogeneity, the usually employed H_2 carrier gas has been replaced by N_2 [1,2]. Here, this method is applied to the growth of strained MQW lasers in the InGaAsP/InP system for the first time. The advantages of N_2 over H_2 with respect to homogeneity are: First, its lower heat conductivity leads to less top- and side-wall depositions. Second, the lower diffusion coefficient of the reactants in N_2 reduces the height of the active gas volume and, therefore, the influence of the walls.
By using N_2 instead of H_2, keeping all other growth parameters unchanged, we could considerably improve the homogeneities of the wavelength, lattice mismatch and layer thickness. Photoluminescence (PL) wavelength mappings of strain-compensated λ=1.55 μm laser structures with 10 QWs grown under N_2 and H_2 atmosphere are shown in the figure. The $\Delta\lambda=\lambda_{max} - \lambda_{min}$, defined here over 40 mm of a 50-mm wafer, has been reduced from 20.5 nm (H_2) to 3.0 nm (N_2) and the standard deviation $\sigma(\lambda)$ from 6.5 to 0.75 nm, respectively, which is a factor of about 7! To our knowledge, this is the best homogeneity value reported so far for InGaAsP grown in any type of MOVPE reactor with any precursors.
Details will be given on the doping efficiency and the electrical and optical properties of layers grown under N_2. Furthermore, we report on excellent characteristics of buried index-coupled and gain-coupled single-mode lasers ($I_{th}\geq$2.3 mA, P=60 mW @ 200 mA, T_0=77 K) and laser arrays based on N_2-grown structures with constant As/P ratio in wells and barriers (CY-lasers), whose compositions and strains are inserted in the figure.



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MATERIALS ISSUES IN GaInP LASER DIODES

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It is recognised that the production of efficient diode lasers requires structures where the active region materials have a high internal quantum efficiency and therefore a low concentration of centres capable of providing non-radiative recombination paths. However, the operation of red-emitting GaInP laser diodes is also influenced significantly by other materials issues, particularly the doping densities and mobility of the cladding layers, often regarded as "passive" components of the structure. This talk will review these aspects through examples of experimental data and computer device simulation, highlighting their special significance for devices operating at short wavelength. The importance of these properties for optimisation of "robust" manufacturable device designs and the appropriate approach to characterisation of these materials for devices will be discussed.

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Low deposition temperature silicon nitride for InP Hererojonction Bipolar Transistor

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Introduction: InP-based Heterojunction Bipolar Transistors are key devices for integration in high speed OEICs for optical fiber telecommunications. The passivation of this component is presently performed with an organic spin-coated film (1,2). To improve the life-time of HBTs, it seems mandatory to passivate the device with a non-organic thin film layer deposited by Chemical Vapor Deposition. Si_3N_4 is a good candidate since it is now widely used for passivation of InP-based components such as photodiodes (3) and field effect transistors. But the extrinsic base surface and the exposed emitter-base junction of HBTs are very sensitive to the quality of the dielectric layer, leading easily to a surface leakage current resulting from the recombination of electron and holes coming to the surface. So, it is necessary to choose a damage free deposition technique, and to have a good control of the deposited material stoichiometry.

Components technology: In this work we have used 2 different plasma enhanced chemical vapour deposition techniques (classical 13.56 MHZ PECVD, and DECR at 2.45 GHz). The test devices were first emitter-base GaInAs(p)-InP(n) heterojunction structures. They were grown on InP by Chemical Beam Epitaxy, and mesa were wet etched. The ohmic contacts were evaporated and annealed under Ar/H_2. The I(V) curves have been recorded prior and after a 500Å SiN deposited layer. The junction ideality factor ($n \approx 1.1$ for non passivated junctions), was extracted from thoses curves.

PECVD 13.56 MHz: This deposition technique is widely used for dielectric layer growth. The ideality factor of E-B diodes is very sensitive to power density and temperature. The shapes of the I(V) characteristics for low forward bias (between 0.1V and 0.5V) show a typical behaviour of surface G-R leakage current. An optimized process at low power-density and low temperature (<100°C) leads to the conservation of a low ideality factor, with superimposition of the I(V) curves before and after passivation.

DECR 2.45GHz: DECR deposition technique is able to form a good dielectric layer at low temperature (<100°C) and without biasing the substrate. Under optimized conditions we have obtained ideality factor for E-B diodes identical before and after Si_3N_4 deposition.

HBT results: The selected processes have been applied to HBTs. In both case the current gain remains identical, indicative of a good E-B junction passivation. A breakdown voltage of B-C diode around 3 volts is observed but this effect is practically eliminated following a low temperature anneal (around 300°C). Finally a SiN layer can be deposited without damage with PECVD and DECR systems, and permits a good passivation of HBTs with good electrical characteristics (ideality factor is around 1.1, the gain at the end of process remains between 95% and 100% of unpassivated components). However, it is well known that very low temperature deposition in classical PECVD leads to porous materials. As DECR SiN is a better quality material (4), DECR technique seems a better choice to avoid evolution of devices characteristics through aging.

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Session 7

Characterisation and Monitoring III

Wednesday, 11.00 a.m – 12.30 p.m.

Chair : D. Look

ELECTRICAL CHARACTERIZATION OF III-V SEMICONDUCTORS USING SCANNING CAPACITANCE MICROSCOPY

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The growth of Scanned Probe Microscopes (SPM) has spawned a host of techniques using the convenience of a small, well defined probe held in proximity to a surface. Measurements which have previously been only possible on the micron and higher scale, may be carried out with nanometer lateral resolution through use of conductive SPM probes. One such measurement is Scanning Capacitance Microscopy (SCM).[1] In this measurement a resonant capacitance sensor[2] is connected via SPM probe to a semiconductor sample. An AC and DC bias are applied to the sample and near surface capacitance variations in response to the bias are measured by the sensor and recorded with the SCM/SPM. The resulting lateral map of capacitance response is acquired simultaneously with topographical variations. The capacitance response varies according to changes in carrier concentration, accumulated charge from traps or strain, variations in dielectric characteristics, etc.

This makes the SCM a valuable tool for fine scale imaging of microscopic photonic devices such as lasers, detectors, and diodes as well as electronic devices such as HBT's and FET's. The images contain information such as carrier concentration and type, barrier height, pn junction location, and interface quality, trap location, frequency, concentration and state. This presentation will contain description and examples of the use, function, and application of Scanning Capacitance Microscopy for III-V semiconductors. Results from the InP, GaN, systems will be highlighted. A discussion of the image contrast mechanisms and interpretation as well as practical limitations will be covered.

Fig. 1 Coulomb scattering centers on edge dislocations are highlighted on epitaxial GaN film. 2.5μm scan.

Fig. 2 Barrier between semi-insulating and n-type InP shown on this laser diode cross-section. 4μm scan.

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CHARACTERIZATION OF SURFACE STATES DENSITY AND SUBSTRATE/EPILAYER INTERFACE STATES IN PSEUDOMORPHIC ALGAAS/INGAAS/GAAS HETEROSTRUCTURES

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It has been previously shown that Hall effect magnetic sensors with a very high performance level can be made using δ-doped pseudomorphic AlGaAs/InGaAs/GaAs heterostructures [1].

For an optimized design of the heterostructure structure, capital figures of merit such as the *thermal drift* of the magnetic sensitivity and its *linearity wrt. bias current* are determined by the quality of both substrate/epilayer (**S/EL**) and epilayer/passivation dielectric (**EL/D**) interfaces. The linearity wrt. bias current drastically depends on the possibility of trapping related to the contamination at the substrate surface prior to epitaxy [2], whereas the value of the residual thermal drift is essentially determined by the EL/D interface states.

In a reverse way, we will show here that Hall effect devices based on δ-doped pseudomorphic heterostructures are a very powerful tool to (i) understand the effect of the deep traps and fixed charges at the S/EL interface on the backgating characteristics of the device, and (ii) determine the density of interface states in a broad energy range at the EL/D interface.

Substrate/epilayer interface

Devices are 4 terminal Hall crosses defined by mesa etching or ion implantation in a MBE grown pseudomorphic heterostructure. The S.I. substrate can be homogeneously biased via an AuGeNi backside electrode. The Hall electron density n_S as well as the tiny substrate current i_X flowing between the channel plate and the backside electrode are recorded simultaneously. The change in the channel electron density n_S is a direct image of the variation of the electric field at the buffer/channel interface, whereas the substrate current i_X is an image of the barrier lowering at the S/EL interface.

The impurity density at the substrate surface was analyzed by SIMS. We investigated the effect of various treatments of the substrate before epitaxy through several types of transport experiments. For a staircase DC substrate biasing, the $i_x(n_s)$ characteristics exhibit a diode-like behavior over several decades of substrate current. Transient and AC experiments were used to investigate the S/EL trapping/detrapping kinetics.

The electronic behavior of the S/EL states, infered from this set of experiments and a model of band bending,, was found to strongly depend on substrate handling procedures.

New method for characterizing the density of surface states

Hall MISFET structures obtained by adding a metal gate on top of the sensor structures were used to study the electron transfer between the 2D channel and the EL/D interface states.

Indeed, the 2D electron density in the channel is a direct image of the potential at the semiconductor surface, and its variation *vs.* gate voltage gives access to the interface state density spectrum.

Using DC gate biasing, the Fermi level could be scanned by at least ±200 meV around the neutral level, and the density spectrum of EL/D interface states was determined in that range.

The screening efficiency of the interface states was dynamically investigated by adding to the gate voltage a small AC modulation with frequency in the 0.1 Hz-50 kHz range. This gives access to the generation/recombination time of the interface states and thus to the pinning energy of the Fermi level wrt. the conduction band edge.

Thanks to the accuracy and resolution of this method, details superimposed to the U-shaped DOS could be resolved. Moreover, its interpretation is more straightforward than e.g. the Terman analysis of conventional C-V experiments in MIS structures.

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Cardiff, June 22-24, 1998

ASSESSMENT AND THE IMPACT OF STRUCTURAL PARAMETERS AND DEVICE TECHNOLOGY ON RESONANT TUNNELLING DIODE CHARACTERISTICS

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ABSTRACT: Quantum tunnelling, an ultra-fast solid-state phenomenon, is of pronounced interest for future high-speed and high-functionality devices [1,2]. However, large area circuit application is still pending partly because of a not yet proven manufacturability. This is mainly attributed to the high sensitivity of the device I-V-characteristics to the layer stack parameters in the monolayer range. Moreover, a non-destructive analysis tool for a direct correlation of layer and device data is not available [e.g. 3]. Recently, a x-ray diffraction method was presented which allows the analysis of final double-barrier resonant tunnelling diode (DB-RTD) symmetrical layer stacks. But this method is restricted to a highly strained barrier-well-barrier configuration [4].

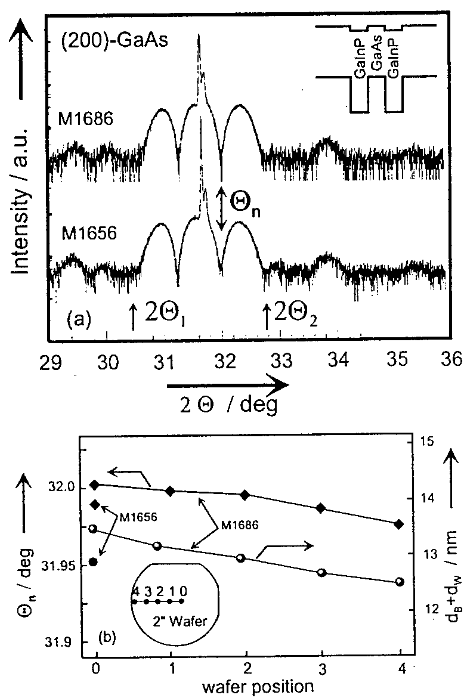

Fig.1: Two nominally identical GaAs/GaInP DB-RTD structures: (a) centre point (200) x-ray rocking curves and (b) Θ_n and deduced d_B+d_W variation across a 2" wafer.

In this work the x-ray method is extended to lattice-matched GaAs-based DB-RTD using the quasi forbidden (200)-reflex. Various III/V-layer structures were grown (MOVPE: GaAs, MBE: InP) and small area DB-RTD were processed. The homogeneity and reproducibility of the layers will be presented and correlated with I-V-characteristics.

The reproducibility of MOVPE growth runs is shown in Fig. 1a. The rocking curves of two nominally identical GaInP-GaAs-GaInP layer stacks for p-type DB-RTD with 30 runs in between are shown. The refracted x-ray intensity of a thin centre symmetric layer structure according to the kinematical formulation after Speriosu can be adopted for an analytical description [4] of i.e. the width of barrier and well from the beat frequency as depicted in Fig. 1a ($d_W + d_B = f\{\Theta_n, \Theta_2\text{-}\Theta_1\}$). From this analytical correlation which holds even in the presence of thick contact layers [4], the measured variation in the centre of the wafers is correlated to a reproducibility of the total thickness of 0.75 nm. The homogeneity of the intrinsic DB-RTD layers across the wafers is evaluated to 1 nm by means of measuring the rocking curves at different wafer locations (cf. Fig. 1b).

Using MBE, an InP-based DB-RTD is developed for digital applications. A low peak voltage and a low peak current is adjusted due to thin barriers (8 ML InAlAs) and thick wells (InGaAs/InAs/InGaAs 4/8/4 ML). A self-aligned small area device technology has been developed allowing an accurate and reproducible device area definition. A study on three nominally identical runs (cf. Table 1) revealed a peak voltage and peak current homogeneity of better than 2.7 % and 5.1 %, respectively, while the reproducibility was within 9.4 % and 6.9 %, respectively. Details on the x-ray method and the correlation to measured I-V characteristics will be given at the conference. This work indicates that a direct correlation of layer and device data for quantum tunnelling devices is available for symmetrical DB-RTD structures. We will show that the aspect of layer data was overestimated in the past, especially if the device dimensions are shrinking according to low-power digital circuit applications [2].

Data	V 101	V 102	V 103	unit
yield	17/17	16/17	19/19	
$V_p (\pm \sigma)$	286 (5)	232 (5)	226 (6)	mV
$I_p (\pm \sigma)$	5.64 (0.13)	5.4 (0.56)	4.66 (0.24)	kA/cm²

Tab.1: Yield and I-V-data (mean value, standard deviation) of 3 nominally identical InP-based DB-RTD (A_E=30 μm²).

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PHOTOREFLECTANCE AS A NON-DESTRUCTIVE ROOM-TEMPERATURE TECHNIQUE FOR ROUTINE TESTING OF PM-HEMT STRUCTURES

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In the context of a comparative study of MBE and MOCVD PM-HEMT structures on 3" GaAs substrates, utilization of photoreflectance indicated that the technique can provide substantial information both nondestructively as well as at room temperature. Concentrating on the structure of the photoreflectance trace below 1.4eV, the technique can provide information on the thickness and In composition of the InGaAs quantum well. In particular, photoreflectance was found to be especially useful for mapping the uniformity over a single wafer and for mapping the reproducibility from wafer to wafer. Distinctive patterns were consistently observed for MBE-grown layers different from MOCVD grown layers. In addition these patterns obtained by room temperature photoreflectance were found to coincide with those obtained by low temperature photoluminescence. Although the two techniques identify different electronic transitions, room temperature photoreflectance can be equally well used as an acceptance test for layer uniformity as low temperature photoluminescence. In probing the reason of non-uniformities, however, photoluminescence provides more information. Experimental results will be presented for both MBE and MOCVD PM-HEMT structures and information extracted from their treatment by modeling in the quantum well.

PHOTOREFLECTANCE EVALUATION OF MOVPE AlGaAs/GaAs MULTIPLE QUANTUM WELLS ON (111)A GaAs

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The growth of compound semiconductors on ⟨111⟩ crystallographic directions has recently attracted significant attention due to their special properties and their possible use for lasers and novel optoelectronic devices. We have recently reported (1) the first successful fabrication of high quality AlGaAs/GaAs Multiple Quantum Well (MQW) structures on (111)A GaAs substrates by the Metal Organic Vapor Phase Epitaxy (MOVPE) process. In this paper we present the application of low temperature Photoreflectance (PR) spectroscopy to assess the abruptness and roughness of the interfaces, the uniformity of the MQW structure as well as its optical properties. PR spectroscopy provides a non-destructive, contactless and highly sensitive evaluation technique.

The 25-period MQW structure with a well length of 55 Å investigated in this work was grown by atmospheric pressure MOVPE at 600 °C. Structural parameters such as the well and barrier lengths, and the Al fraction were accurately determined from a High Resolution X-Ray Diffractometry (HRXRD) study. A theoretical computation appropriate for ⟨111⟩ oriented structures was used to obtain all the confined electron and hole energies and thereby interpret the PR analysis. The PR spectrum shows four features corresponding to the different transitions within the well, and the AlGaAs-related peak at 1.862 eV which provides the Al fraction in the barriers. The PR spectrum is well explained by considering the allowed and weakly allowed transitions between the two E1 and E2 electron states, the three HH1 to HH3 heavy hole states and the LH1 light hole state in the wells. The theoretically calculated transition energies are in very close agreement (±2 meV) with those experimentally obtained from the PR spectra even up to the highest possible transitions for the wells. From a detailed Monolayer (ML) analysis of the electron and hole energies it is concluded that the quantum well interfaces have a ±1 ML fluctuation over the 25 periods and that the interfaces are very smooth, abrupt and uniform. We also found an excellent agreement between the PR and HRXRD results for the structural parameters, such as well length and Al fraction in the barriers.

The Photoluminescence (PL) measurements were also used to further assess the optical quality and period reproducibility. The PL spectrum exhibits a single emission peak corresponding to the transition between the E1 and HH1 states. The full width at half maximum (FWHM) is 12.5 meV, which corresponds to at most a ±1 ML fluctuation throughout the 25-period MQW in agreement with the PR analysis. This FWHM is the best value reported to date for an AlGaAs/GaAs MQW structures grown on (111) GaAs either by MBE or MOVPE.

[1] A. Sanz-Hervás, Soohaeng Cho, O.V. Kovalenkov, A. Majerfeld, C. Villar and B. W. Kim. Proceedings of the ISCS97, San Diego, California, USA, September 1997. To be published by the IEEE.

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Poster Session A

Tuesday, 11.00 a.m – 12.30 p.m

CHARACTERISATION OF III-V OXIDE DESORPTION BY SURFACE PHOTOABSORPTION

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The thermal desorption of the oxides of several III-V substrate materials has been investigated by surface photoabsorption (SPA). In this preliminary study GaAs, GaP, GaSb, InAs, InP and InSb substrates were slowly heated under molecular hydrogen, with and without various group V precursors (e.g. arsine, which may be a source of atomic hydrogen), to desorb surface oxides prior to metalorganic vapour phase epitaxial (MOVPE) growth. SPA was performed by probing these surfaces with *p*-polarised 670 nm laser radiation throughout desorption and the reflected beam intensity constantly monitored. Such an arrangement allows the oxide desorption to be observed clearly, non-destructively and continuously.

MOVPE requires semiconductor nucleation of very high structural integrity. It is of primary importance, therefore, that surface oxides are removed efficiently whilst bulk stoichiometry is retained at the surface and minimal damage introduced. At present, oxide desorption mechanisms relevant to MOVPE are somewhat unclear and a better understanding of the processes can only improve the quality of growth.

Substrates were either used 'epiready' or after further preparative procedure in order to change the surface conditions, e.g. oxide type/thickness. Furthermore, comparisons have been made between substrates from different manufacturers. This has allowed oxide thicknesses and desorption activation energies to be estimated and some chemical assignments of oxides to be tentatively made. The role of atomic hydrogen in deoxidation at atmospheric pressure is also discussed. This wide ranging survey of different III-V substrates and different surface treatments therefore provides data that will, it is hoped, lead to an improved understanding of surface oxides and their desorption for the purposes of semiconductor growth.

MAGNETOPLASMA RESONANCES IN MICROSTRUCTURES WITH TWO-DIMENSIONAL ELECTRON GAS AT 77K

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Magnetoplasma resonances in microstructures with two-dimensional electron gas (2DEG) are intensively investigated [1]-[4]. The investigations of plasma resonances in various microstructures with 2DEG (arrays of disks [1,2], ellipses [3], and rings [4]) are based on the method of transmission spectroscopy over a wide range of frequencies (28÷600 GHz). The sizes of samples being studied in these investigations were less than cross-section of the waveguide. These experimental conditions do not allow the derivation of theoretical expressions for describing the magnetic field dependences of the reflection and the transmission coefficients. Moreover it was necessary to cool samples down to liquid helium temperature for the observation of magnetoplasma resonances (as a minimum of the transmittance).

In this report we present results of experimental research of the magnetic field dependences of the dynamic conductivity of 2DEG in GaAs/AlGaAs heterostructure and 2D array of squares (30×30 μm^2) fabricated from that heterostructure. The experiments are performed at microwave frequencies from 55 to 78 GHz and at **liquid nitrogen temperature**. We derive theoretical expressions for the magnetic field dependences of the transmission and the reflection coefficients from the sample with 2DEG bridging the waveguide completely and for the case when only the basic mode TE_{10} propagates in the waveguide. A comparison of calculations and experimental results has been made.

References

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FIELD ENHANCED CAPTURE OF ELECTRONS BY EL2 CENTRES IN GaAs

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It has been known for some time, especially from work on nuclear particle detectors, that a Schottky diode fabricated on a semi-insulating GaAs substrate produces an anomalous electric field under high reverse biases. Instead of observing the expected field profile beneath the Schottky contact, i.e., one that drops linearly, one observed a region where the field is nearly constant and then falls steeply to zero. This means that in the flat high-field region there is very little net charge. This is unexpected since SI GaAs has an abundance (10^{16} cm^{-3}) of the deep donor EL2 and one would normally expect these centres to ionise. To explain this observation it has been suggested by previous groups that EL2 centres acquire a rapidly increased capture cross section when the electric field exceeds a critical value of approximately 1 V μm^{-1}.

We have performed capacitance-voltage analysis upon a uniform as-grown substrate, Te-doped at 4.10^{15} cm^{-3} and successfully reproduced the anomalous extracted apparent carrier concentration profile using data that assumes a population of 2.10^{16} cm^{-3} EL2 to refill at a critical field of 7×10^{6} V/m. We speculate that the observed "field enhancement" of capture cross section strongly dependant upon the electrons position within the E-k diagram. The field at which carriers with the favoured E-k relationship occur being lower in the nominally undoped detector material than in the lightly n-type samples that we investigated.

Investigation of Photo-Stimulated Diffusion for Creation of Thin Doped Layers in III -V Semiconductor Compounds.

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The creation of high-quality thin doped layers in semiconductors is the most important task for microelectronics. The existing models based on high-temperature processes (including ion implantation by annealing) have a lot of drawbacks due to prolonged high-temperature processes: bad control, impossibility of adjustment of the diffuser penetration depth, washing out of the doped region edges (absence of marked boundaries) etc.

This work is devoted to investigation of relatively low-temperature photo-stimulated diffusion (PSD) processes for creation of thin doped layers in III-V semiconductor compounds (GaAS,GaAlAs,GaP). A possibility of a significant reduction of temperature and especially of time (up to several seconds) of diffusion processes is shown. The short duration of the processes significantly decreases the above mentioned drawbacks of the diffusion processes. The application of this technological process is especially important for III-V semiconductor compounds.

New methods of pulse-photon treatment (PPT) of semiconductors are proposed for formation of:

- ohmic contacts to GaAs and GaAlAs, GaP light emitting structures;
- p-n junction using PSD of Zn into p-GaAs;
- p+ and n+ regions to p- and n- GaAs (Zn and Ge PSD respectively);
- intercomponent insulation by Cr PSD into GaAs epitaxial structures.

Some theoretical considerations for understanding these phenomena are given : ionization (rather than thermal) processes are predominant, which results in reconstruction of the quantum state of the electron subsystem and in stimulation of diffusion processes near the semiconductor-metal interface. Therefore at PPT to GaAs Ga vacancies are essentially created.

SCANNING PROBE MICROSCOPY CHARACTERIZATION OF SURFACE SEMICONDUCTOR NANOSTRUCTUTERS

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We report on the atomic force microscopy (AFM) application for imaging and evaluation of InGaAs dot structures on GaAs surface and on the combined the atomic force microscopy / scanning tunnelling microscopy (STM) analysis of the multilayered ZnSe structures on GaAs wafer in ambient conditions. AFM tapping mode of operation is used for dots imaging alongside with phase contrast technique. Cleaved multilayerd ZnSe structures were probed by AFM and STM. AFM included surface morphology imaging with simultaneous lateral forces relief imaging. The results obtained in different modes of AFM/STM operation have been compared with one another to get rid of artefacts. The two-dimensional and three-dimensional images were analysed to estimate the size of the observed nanostructures. The advantages of the SPM and some aspects of AFM/STM imaging and contrast in different modes of operation are discussed.

Multiple Quantum Well GaAs/AlGaAs Solar Cells : Transport and Recombination Properties by means of EBIC and Cathodoluminescence.

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Recently, multiquantum well (MQW) solar cells have been reported as a new approach to built high efficient cells in Photovoltaics. Indeed, efficiencies of 19.7 - 23% have been obtained for tandem $GaAs/Al_{0.37}\,Ga_{0.63}As$ cells measured at AWO (Air-Mass Zero). In its simplest design, the MQW is localised in the undoped region of a p-i-n solar cell. Hence, the electron-hole (e-h) transport and recombination properties play a fundamental role in the quantum efficiency of the photovoltaic device. In this contribution, we evaluate the transport and recombination properties of MQW $GaAs/Al_{0.24}Ga_{0.76}As$ solar cells by means of Electron-Beam-Induced-Current (EBIC) and Cathodoluminescence (CL). Experimental EBIC/CL measurements are performed on two identical solar cell structures, one with (*A*) and the other with (*B*) MQW in the i-region. Comparing the experimental date to theoretical predictions the recombination rate in the quantum wells is quantified.

For EBIC and CL quantitative analysis, our approach consists in first estimating the extent of electron-hole pair generation by a Monte Carlo procedure. Second, the Poisson and e-h current density continuity equations are resolved applying a second consistent iterative finite difference method. The contribution of the wells to the EBIC/CL is modelled from quantum mechanical calculations solving the Schrödinger equation in the effective mass approximation.

From measurements on the solar cell B, the minority carrier diffusion length at both p- and n-sides and the surface recombination velocity is estimated. Using the latter, the e-h recombination rate at quantum wells of *A* is estimated for different injection levels. The recombination phenomena in terms of recombination lifetime and carrier escape hopping out the quantum wells is discussed.

In conclusion, a quantitative EBIC/CL characterisation of MQW GaAs/AlGaAs solar cells is presented. EBIC and CL studies supported by numerical calculations are shown to be a powerful tool to evaluate local carrier behaviours as e-h quantum well capture, e-h quantum well escape and local e-h recombination rate.

COMPARISON OF InGaAs/InAlAs ELECTROABSORPTION MODULATOR STRUCTURES ON (100) AND (111) InP SUBSTRATES

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The piezoelectric fields developed along the [111] direction in strained III-V quantum wells may be explored for the realization of blue shift electroabsorption modulators. Devices based on multiple quantum well (MQW) heterostructures of InGaAs/InAlAs are very interesting since they allow operation in the region of $\lambda \approx 1.55\mu m$ and can be grown conveniently by solid source Molecular beam Epitaxy (MBE). This, however, requires that excellent quality heterostructure material will be grown on (111) InP substrates.
We have investigated the MBE growth of InGaAs/InAlAs heterostructures on vicinal (111)B InP substrates. Epitaxial layers were analyzed by X-ray Diffraction, Transmission Electron Microscopy (TEM) and optical spectroscopy measurements. Electroabsorption pin MQW heterostructures were grown on both (100) and vicinal (111)B InP substrates, pin diodes were processed and their photocurrent spectra at 300K were compared. The photocurrent spectra of (100) structures exhibited many excitonic transitions but rather featureless spectra were recorded on the (111) structures. Applied reverse bias resulted to a strong red shift of the absorption edge on (100) but no essential shift was observed for (111). These results are related to quantum well variations resulting from InAlAs surface step-bunching and InGaAs, InAlAs compositional modulations on (111) InP. Thus, material growth problems limit the development of blue shift InGaAs/InAlAs electroabsorption modulators but evidents exist for a growth window that may allow device quality layers.

InGaAs LAYERS OF HIGH QUALITY GROWN ON PATTERNED GaAs SUBSTRATES WITH TRENCHES

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$In_xGa_{1-x}As$ ternary semiconductors are very promising materials for detectors in the near infrared region (0.87 - 3.5 μm). However, misfit dislocations are formed at the interface between an InGaAs layer and a GaAs substrate, and the threading dislocations penetrate into the layer from the substrate. As a result, the quality of the grown layer becomes poor.

To reduce the dislocation density, we grew $In_xGa_{1-x}As$ layers on SiN_x-masked GaAs (111)B patterned substrates with trenches of 1 mmϕ in diameter by the liquid phase epitaxial method, and demonstrated that the grown layer made a bridge across the trench [1]. This paper describes the influence of trench depth and In composition on the layer quality.

(1) The effect of trench depth;

$In_xGa_{1-x}As$ (x=0.06) layers were grown on GaAs patterned substrates with trenches of 0, 20, 40 and 50μm in depth for 3 hours at a cooling rate of 10°C/h from 800°C. The layer across a trench less than 20μm in depth contacted the trench bottom, but the bridged layer was formed when the depth of a trench was more than 40μm.

(2) The effcet of In composition;

$In_xGa_{1-x}As$ (x=0.06, 0.10, 0.15) layers were grown on the substrate with the trench of 40μm in depth. Their lattice misfit ratios were 0.43, 0.71, and 1.07%, respectively. The growth morphology of each surface of grown layers was very fine. Many etch pits were recognized in the layers grown near the wall of the trench. The etch pit density (EPD) was more than 10^8 cm^{-2}. However, the EPD reduced to $10^4 \sim 10^5 cm^{-2}$ in both layers inside and outside of the trench. Therefore, the bridged layer was not suffered from the influence of misfitness. The results obtained here clearly suggest that even if the x value of In composition increased to 0.15, the growth of high quality crystals is possible by using substrates with trenches of 40 μm in depth.

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CONTACTLESS MAPPING OF *MESOSCOPIC* RESISTIVITY VARIATIONS IN SEMI-INSULATING SUBSTRATES

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Contactless resistivity mapping (COREMA) [1] has been established as a convenient technique to measure the electric resistivity of semi-insulating compound semiconductor wafers quickly and nondestructively. The method relies on time-dependent charge measurement with a noncontacting capacitive probe. Full wafer images can be generated and are evaluated absolutely with respect to average resistivity and lateral fluctuations, allowing effective control of the ingot growth process and subsequent homogenization by annealing.

The lateral resolution of existing equipment and reported results is on the order of mm^2, which is adequate to evaluate macroscopic variations, but insufficient to discern mesoscopic resistivity fluctuations, e.g. caused by the cellular distribution of dislocations in LEC GaAs. The study of such mesoscopic inhomogeneities requires a lateral resolution better than 100 μm, thus far only realized by destructive point contact topography (PCT) [2].

By improving probe design and data acquisition, we are now able to generate COREMA topograms with a lateral resolution of about *30 μm*. Absolute values of the resistivity variations between cell wall and cell interior are obtained, giving clear images of the mesoscopic cellular structure even for well homogenized material with a residual fluctuation of some percent only. The lateral patterns and the fluctuation amplitudes are compared with corresponding PCT images subsequently generated for the same probe area. In general satisfactory agreement is observed. Remaining discrepancies will be discussed, taking into account the different lateral and vertical probe current distributions generated by COREMA and PCT.

Images and statistical evaluations obtained for state-of-the-art substrates of leading wafer suppliers will be presented and discussed.

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Analysis of hopping conduction in device-like structures on nonstoichiometric molecular beam epitaxial GaAs

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It is well known that the conduction in nonstoichiometric (NS) MBE GaAs is influenced by the hopping within an arsenic antiside defect band. In general, the conduction can be described by mixed regime with different band and hopping contributions to the total conduction, $\sigma=\sigma_{band}+\sigma_{hop}=\sigma_{b0}T^{3/2}\exp(-E_{dd}/kT)+\sigma_{h0}\exp(-\varepsilon_3/kT)$. In unannealed NS GaAs grown around 200 °C the As_{Ga} density is extremely high (about 10^{20} cm^{-3}) and therefore the hopping strongly dominates. Such layers show low resistivity (less than 100 Ω cm) and extremely low mobility (less than 1 cm^2/V s) at room temperature. The hopping (i.e. the As_{Ga} density) is reduced by increasing growth temperature, as well as by annealing. However, in annealed NS GaAs grown at 350 °C, which has the resistivity of about 10^7 Ω cm and the mobility of about 10^3 cm^2/V s, the room temperature hopping and band contributions are still comparable. These results follow from the van der Pauw measurements using NS GaAs separated from the substrate. On the other hand, in device-like NS GaAs structures, i.e. in structures with micrometer contact separation, another conduction behaviour due to the space-charge effects can be found. We found for the first time that in such structures the hopping conduction can be essentially suppressed.

In this study the properties of NS GaAs in which the current flows vertical to the layer surface are studied. Samples with as-grown and annealed NS GaAs of different thicknesses grown at various temperatures are used. The conductivity is evaluated from low-field Ohmic part of the I-V characteristics measured at various temperatures. The carrier density and mobility are obtained from the temperature dependent geometric magnetoresistance (GMR) measurements. Properties of such 'vertical' structures are compared with data we obtained before on 'planar' structures, i.e. by van der Pauw measurements.

Results obtained in this study can be summarized as follows:

i) The room temperature conductivity of as-grown and annealed 'vertical' NS GaAs is about 100-times smaller in comparison to that measured on 'planar' structures prepared at similar conditions.

ii) From the fitting of the experimental $\sigma=f(T)$ dependences it follows that the same band contribution σ_{band} (with the same E_{dd}) but much lower hopping contribution σ_{hop} exist in 'vertical' structures.

iii) From independently performed GMR measurements it also follows that the hopping is suppressed – the temperature dependences of the carrier density show such typical behaviour and the room temperature carrier mobilities are enhanced (e.g. from 2.5 to 1500 cm^2/V s in particular NS GaAs).

iv) Observed suppresion of hopping is explained by electric field overshoot due to the space-charge effects in the vicinity of the NS GaAs junction and resulting conditions at which the energy difference between hopping sites is much higher than the maximum phonon energy.

v) These results needs to be considered at the design of NS GaAs based devices and an example will be presented: a photodetector with 550 GHz bandwidth which is higher than previously reported.

Be DIFFUSION IN InGaAs, InGaAsP EPITAXIAL LAYERS AND ACROSS InGaAs/InGaAsP, InGaAs/InP HETEROINTERFACES.

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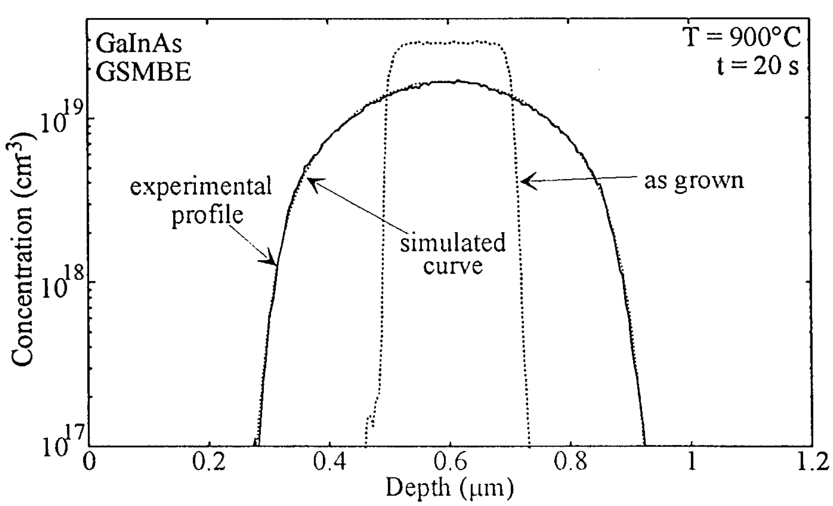
The subject of this work is the simulation of Be diffusion during post-growth rapid thermal annealing (RTA) across heterointerfaces InGaAs/InGaAsP, InGaAs/InP and in InGaAs, InGaAsP layers grown by gas source molecular beam epitaxy (GSMBE).

This diffusion may occur during thermal treatments of InP/InGaAs double-heterojunction bipolar transistors (DHBTs) with a step-graded InGaAsP collector, which contributes to limit the frequency performances of these devices.

The observed secondary ion mass spectrometry (SIMS) concentration distributions, obtained for annealing cycles with time durations of 10 s to 5 min and temperatures in the range of 700-900°C for doping concentration of $3 \times 10^{19}\ \mathrm{cm}^{-3}$, could be explained by Kick-Out mechanism considering the neutral Be interstitial species and positively charged group-III self-interstitials.

Very good agreements were obtained between our depth profiles and the corresponding simulated distributions, obtained from the differential equations solved by an explicit finite-difference method taking into account Fermi-level and electric build-in field effects.



Be diffusion in InGaAs homostructure.

It was also observed that the Be diffusion in heterostructures is affected by phenomena of gettering and segregation.

THE CHANGE OF ROTATION ANGULAR DEPENDENCE (AD) OF THE SECOND HARMONIC INTENSITY OF CdTe EPILAYERS ON GaAs(100) SUBSTRATE AT THE INITIAL STAGE OF HETEROEPITAXY.

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In the recent work L. Berlouise et al observed the rotation anisotropy of II-VI epilayers on GaAs substrate [1]. The authors writes, that observed anisotropy arisen from vicinal surface of II-VI epilayer, followed the substrate vicinal surface (the (100) substrates tilted 2° towards the <110> direction were used).

We observed the change of rotation dependence by second harmonic generation (SHG) at the initial stage of molecular beam epitaxy of CdTe on GaAs (100) substrates.

The samples have been prepared at MBE-machine by heating until oxide removing and following growth of cadmium telluride with few monolayers thickness. Then the samples were investigated by means of SHG.

We used the normal incident of laser beam and the transmission scheme of SHG technique that we previously described at our report on EXMATEC'96 [2]. To measure changing of rotation angular dependence (AD) of the second harmonic intensity the rotation of polarisation plane of exciting radiation were used.

We observed the change in AD of the samples in comparison of AD of the GaAs substrates measured before growth of CdTe. The measured dependencies and it's analysis is presented.

More of them, such changes were observed at the stage of interaction of tellurium with GaAs substrate surface. For these subject we heated the GaAs substrate in tellurium molecular beam. The surface reconstruction caused the interaction of tellurium with GaAs surface, registered by means of reflection high energy electron diffraction (RHEED).The angular dependencies measured after and before heating of the samples in Te_2 molecular beam were compared. This change of AD can be explained by Ga-Te compound (for example, Ga_2Te_3) formation.

The change of AD of the samples with CdTe with few monolayer thickness were compared with the AD of the samples, heated in tellurium molecular beam. If CdTe growth started from the GaAs surface containing Te and may be characterized by subsequent surface reconstruction the AD of such sample follows the AD of the surface of GaAs substrate, modified by the interaction with Te.

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ELECTRICAL AND MORPHOLOGICAL PROPERTIES OF ORDERED $In_xGa_{1-x}P$

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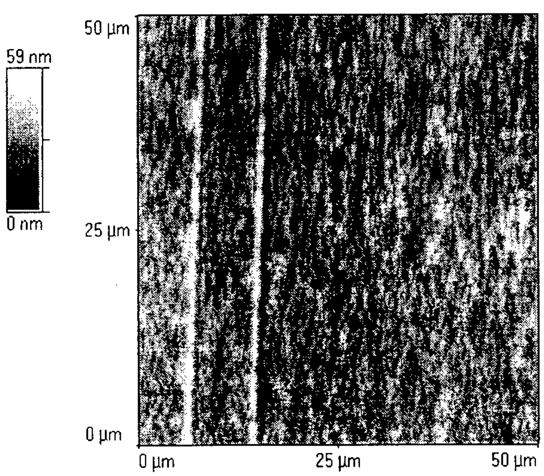
In recent years extensive efforts have been devoted to the growth, optimization, and characterization of $In_xGa_{1-x}P$ epitaxial layers lattice matched to GaAs. InGaP layers have been proposed as a very promising barrier material to GaAs with a good possibility to substitute AlGaAs in electronic and optoelectronic devices, since AlGaAs contains a large concentration of DX-centres and it is highly reactive with oxygen. Using the InGaP/GaAs material system is partially hindered by the occurrence of ordering in InGaP. In an ordered semiconductor crystal the solid composition is modulated along a particular direction with a period of several lattice spacings. This results in the formation of a superlattice structure in the semiconductor alloy, which has a very important influence on practically all mechanical, electrical and optical properties of the material.

We have studied the electrical and morphological anisotropy of $In_xGa_{1-x}P$ epitaxial layers lattice matched to GaAs with respect to the application of these layers in quantum-wire structures. The epitaxial layers were prepared in an Aixtron AIX200RD equipment with a horizontal low pressure reactor at the temperature interval between 520 and 760 °C. The source materials for the growth of GaAs and InGaP were arsine (AsH_3), phosphine (PH_3), trimethylgallium (TMGa) and trimethylindium (TMIn). The total pressure inside the reactor of 50 mbars was chosen as an optimal value for all growth temperatures with respect to the surface morphology and uniformity of the layers grown. Palladium-diffused hydrogen was used as the carrier gas.



Morphology of the grown layers was studied by AFM. An AFM plan view image of an ordered sample is shown in Fig. 1. The surface structure of this InGaP layer consists of elongated domains oriented along the [110] direction. These domains are relatively large. The biggest are about 1-2 mm long and 0.5 mm wide. The surface roughness is up to 60 nm high. This layer was grown at 600 °C . On the other hand, no presence of similar domains was observed on samples with a very low degree of order. Surface roughness on these samples was under 3 nm.

Electrical properties of the grown layers were evaluated using a Van der Pauw method. In the case of large anisotropy in electrical properties a four probe method for resistivity measurement was used. It was observed that ordering influenced the resistivity ratio in the [110] and [1-10] directions up to 100 depending on growth conditions.

CAPACITANCE-VOLTAGE PROFILING OF INHOMOGENEOUS MULTIQUANTUM WELL STRUCTURES AlGaAs/GaAs.

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A simple and convenient method of calculation of the capacitance-voltage (C-V) dependencies and majority carrier concentration profiles in inhomogeneous multiquantum well structures (MQWs) is developed and applied to the study of AlGaAs/GaAs MQWs. The problem of the influence of various types of inhomogeneities on concentration profiles is considered. The theoretical model of an MQW structure takes into account the inhomogeneity of layer thicknesses, barrier alloy composition, layer doping levels, and the existence of local in-plane nonuniformities resulting e.g. from the presence of some localized electrically active species. The analysis of calculated data enables us to draw the conclusions on the role of various types of inhomogeneities on capacitance parameters of the investigated structures. The model reveals the reasons for the previous discrepancies of the experimental concentration profiles with the theoretical ones obtained disregarding the effects of inhomogeineity in real MQWs. The good fit of the experimental data by the proposed model verifies the model assumptions, and enables the use of the model for the analysis of inhomogeneous multilayer structures.

Study of Dopant-Dependent Band Gap Narrowing in Compound Semiconductor Devices

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Band gap narrowing is one of the crucial heavy-doping effects to be considered for bipolar devices. In case of HBTs, where discontinuities in the energy levels appear, the correct modeling of the energy barriers has basic importance for studying the device performance. Using the physically-based approach from [1], we present a new band gap narrowing model which considers the semiconductor material and the dopant species for any temperature. As a particular example we present in Fig. 1 the results for Si-doped GaAs and P-doped Si. Note the stronger band gap narrowing at 77K, caused by higher degeneracy. Neglecting this effect results in an error of about 50%.

As a particular example we studied with MINIMOS-NT, our two-dimensional device simulator with approved capabilities of simulating devices with complex structure the electrical behavior of graded composition Si/SiGe HBT and AlGaAs/GaAs HBT using a hydrodynamic transport model. Our investigations were performed in a comparative way for different dopant species and temperatures, using the new band gap narrowing model and old ones, which neglect differences in the dopant species. In Fig. 2 we present the Gummel plots for Si/SiGe HBT at 77K and 300K obtained with the model of Slotboom et al.[2] (Mod.1) and with our new model (Mod.2). Note the significant difference in the current density values at 77K, resulting for Mod.2 in higher current gain, which is confirmed by experiments.

In summary, a new band gap narrowing model is presented and its impact on the HBT device performance is studied.

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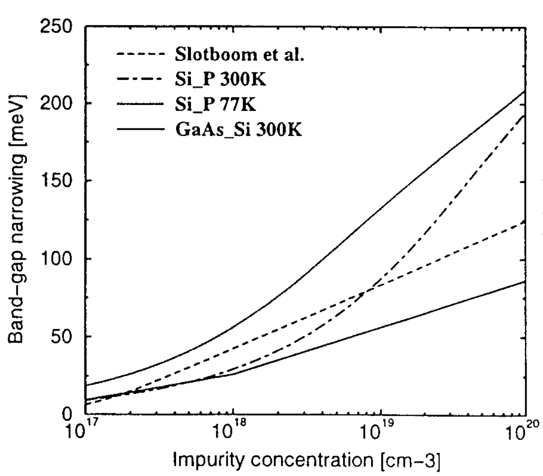

Figure 1: Band Gap Narrowing vs. Impurity Concentration

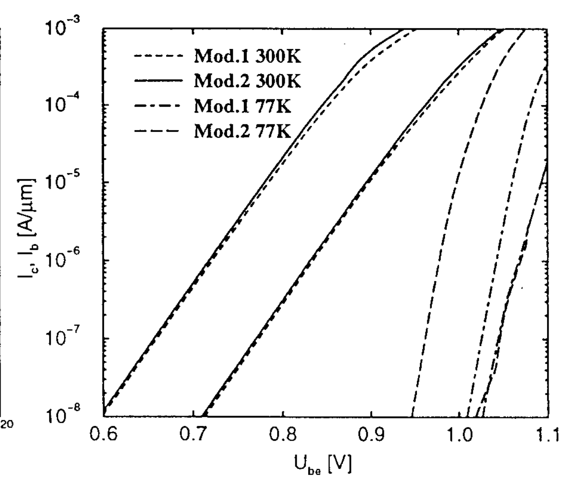

Figure 2: Gummel Plots at $V_{ce} = 2V$ Mod.1 and Mod.2

Influence of GaSb Substrate Qualities on the Properties of GaInAsSb Films grown by MOCVD

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In order to obtain good property GaInAsSb films grown by MOCVD the GaSb substrate qualities are very important.. In this paper the influence of surface morphology, optical and electrical properties of GaSb substrate wafers was presented for obtaining good quality MOCVD GaInAsSb Epilayers.

Te- doped (100) GaSb substrates were used for experiments. The surface treatments of GaSb wafers prior to MOCVD growth of GaInAsSb films include " exsitu " chemical etching, annealing under TMSb flow at growth temperature and growing a GaSb buffer on GaSb substrates

The surface morphology of etched GaSb wafers and the MOCVD GaInAsSb epilayers strongly depends upon the qualities of GaSb substrates, because some defects which originate in GaSb wafers appear and propagate in the case of the proper chemical treatment and, thus, degrade the morphology of substrates and the surface of the epilayers

The GaSb wafer qualities were studied before and after growing GaInAsSb epilayers grown by MOCVD using PL, DCXD, FTIR and electrical properties. It has been shown that the different kinds of GaSb wafers have different PL, DCXD and FTIR spectra as well as electrical properties. The heat treatment of etched and cleaned GaSb substrate in MOCVD reactor under TMSb flux can led to change the conductive type from n- to p- for several GaSb wafers, which indicates they exhibit the bad thermal stability.

The GaSb wafer with high transmittance (>40 %), abrupt adsorption edge at ~ 5700 cm wave numbers and smaller FWHMs of DCXD (< 20arcsec) and PL spectra (~ 20 aresec) as well as a good thermal stability of electrical properties is suggested to be used as the substrates for obtaining the good quality GaInAsSb epilayers. And, then, the high performance 1.8 ~ 2.4 um PN photodetectors (detectivity = ~ 10^{10} cm.Hz$^{1/2}$/W at room temperature) could be achieved.

MICROSCOPIC INVESTIGATION OF INTIMATE METAL-$In_xGa_{1-x}As$ DOT CONTACTS OBTAINED AT ROOM AND CRYOGENIC TEMPERATURES

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The optimization of metallisation strategies for the fabrication of electrical contacts is currently of great interest in III-V based technology. In particular, accurate control of the rectification properties and contact resistance by the appropriate choice of metal type and growth conditions is crucial to assure reproducibility of contact behaviour and hence device performance. Recently, effort has been devoted to the improvement of low Schottky barrier heights of metal-$In_xGa_{1-x}As$ contacts, driven by the applications of this material in high frequency and optoelectronic domains,[1,2]. The influence of the metallisation procedures on the final properties of intimate metal-InGaAs Schottky contacts is well documented,[3,4] the metal deposition temperature being one of the most significant parameters.

In this work, we present the microscopic characterization of intimate Au and In contacts formed on (100) $In_{0.53}Ga_{0.47}As$ surfaces. The InGaAs epilayers were 1μm thick, grown by molecular beam epitaxy on (100)InP substrates, and non-intentionally doped, to yield a carrier density $n \approx 1\times10^{16}cm^{-3}$. The metals were deposited onto each sample wafer through a shadow mask, giving approximately 20 circular diodes of radius ≈ 0.325 mm, of approximately 400Å thickness, per metal. Metal contacts were formed by deposition under three different surface preparations, *(i)* on atomically clean samples maintained at 77K, *(ii)* on atomically clean samples at room temperature (294K) and *(iii)* at 77K on samples removed from UHV conditions following growth and subjected to a wet chemical etch.

Previous I(V) measurements indicate that for the case of intimate In-$In_{0.53}Ga_{0.47}As$(100) contacts, barrier heights may be enhanced from 0.30 eV for diodes formed at room temperature to 0.45 eV by metal deposition on samples cooled to 80K. No such effect has been observed in Au- or Cu-$In_{0.53}Ga_{0.47}As$(100) contacts formed under similar conditions. In the present work, the metal-semiconductor interfaces are examined by coventional and high resolution Transmission Electron Microscopy. The configuration of these intimate contacts and the correlation with the Ohmic and Schottky behaviour are discussed in terms of the interfacial reactions resulting from the differing deposition conditions. Atomic force microscopy characterization of the metal surface is also presented.

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Si_3N_4/Si HETEROSTRUCTURES USED FOR FIELD EFFECT ENHANCED PHOTOCONDUCTIVITY IN PbS THIN FILMS

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Lead sulphide (PbS) is a well-known material used for infrared detection. The permanent enhancement of the deposition process had allowed the manufacturing of highly sensitive photoresistors with various applications in industry and defence. Further enhancement of the detection characteristics by modifying the material properties is no longer possible and other approaches have to be tried. The requirement of PbS based detectors integration with Si technology give us the idea to use the field effect for PbS photoconductivity enhancement. Some attempts were made either depositing a PbS film on a ferroelectric ceramic[1] or using more complex heterostructures including as insulating layer SiO_2 [2] or lead titanate ($PbTiO_3$)[3]. In both cases an important variation of the PbS photoconductive signal with the voltage applied on the gate electrode was observed. However, the SiO_2 film is very sensitive to the excess charges and breakdown very easily while the lead-titanate is a non-linear dielectric and implies complex mechanisms of charge transfer, which lead to different behaviours of PbS film for different wavelengths. Thus, other insulating materials have to be tested in order to optimise the performances of the PbS field effect controlled photoresitors. One of these materials is the silicon nitride (Si_3N_4).

Si_3N_4 thin films were deposited by low-pressure chemical vapour deposition (LP-CVD) on (100) single crystal Si wafers, both n and p type, with MOS resistivity (1-10 Ωcm). The thickness of the film was about 2000-2500 Å and the quality of the Si_3N_4/Si interface was tested by C-V measurements. The C-V curves had revealed the presence of a fixed charge, located either in the insulating layer or at the interface, leading to a shift of about -10 V in the characteristics no matter the Si_3N_4 was deposited on n or p type Si. For the Si_3N_4 films deposited on p type Si a hysterezis was observed at frequencies below 10 kHz, suggesting the presence of a mobile charge in the insulating layer. The estimated value of the dielectric constant is 5-6. This is a little lower than the value reported in the literature, probably due to the presence of an interface layer with a different dielectric constant or due to the non-stoichiometry of the insulating film (SiN_x instead of Si_3N_4).

The Si_3N_4/Si were used as substrates for the deposition of the PbS film. This was deposited by a chemical method on the surface of the insulating layer and a three electrode configuration was defined for photoconductivity measurements, with the gate electrode on the back side of the Si substrate. The preliminary results show an enhancement of about 25 % of the photoconductive signal on the entire wavelength range (1-3 μm) and a greater stability than in the case of the PbS/SiO_2/Si heterostructures. Further studied are need to optimise the geometry and to clarify the physical processes taking place at the two interface during illumination.

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EXMATEC '98, 21-24 June 1998, Cardiff, UK

High presision reflectometry : A method to evaluate the performances of photonic components and circuits

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ABSTRACT

With increasing complexity of monolithic integration technologies on InP substrates, the development of simple, nondestructive and accurate methods to diagnostic the performances of individual components (active and passive) and the transition regions between them (for example, butt-joints) in processed photonic circuits is becoming increasingly necessary. In this regard, we show here that the high precision reflectometer marketed by Hewlett Packard (HP 8504B) is a well suited instrument to assess not only the quality of transitions but also the performances of individual components in the circuits prior to mounting.

The high precision reflectometer functions on the principle of Michelson's interferometer and uses the techniques of "white light" by operating with a « low coherence » light source at a wavelength well suited for the analysis of optical communication devices (1.3 or 1.55 μm). It is highly sensitive to small refractive index (n) discontinuities and measures return losses (or very small reflection losses) with a dynamic range exceeding 80 dB. The output data, consequent of multiple reflections (to and fro) in the device under test, depict the amplitude of return losses at each reflection (as Y-axis) plotted against an equivalent distance traveled by the incident light in air (as X-axis). Such data, as shown by the examples here, is exploited to evaluate the material refractive index, to detect and locate the anomalies in propagation caused either by defects or by transition regions (butt-joints) and also to extract useful information on losses induced by waveguide geometry (for example, curved guides .vs. straight guides, as a function of guide's radius of curvature, R_c).

All waveguide-based components, discrete or integrated, studied here were grown on InP substrates and often contained a InGaAsP quaternary guiding layer sandwiched between two InP cladding layers. After a brief description of the basic principles of reflectometer operation, we first describe the procedure how the data recorded on simple straight waveguides can be exploited to evaluate the guide (see **fig. 1**) and substrate (see **fig. 2**) material refractive indices. Next, some examples of data illustrating the detection and location of propagation anomalies caused by defects in the guiding layers will also be presented and discussed. Later on, we present data recorded on curved guides (R_c is varied in the range 10 to 3000 μm) to demonstrate in two different ways how this instrument can be usefully employed to determine experimentally the optimal R_c value for minimum losses. First, by evaluating the refractive index difference (Δn) with respect to a straight guide for unit curvature (see **fig. 3**) and second by measuring the return losses, both as a function of R_c (see **fig. 4**). Finally, through examples of data recorded on butt-jointed photonic integrated circuits, we illustrate the usefulness of this instrument to evaluate the reflection and coupling properties of the butt-joints.

TFTS IN POLYCRYSTALLINE SILICON : HIGH PERFORMANCES OBTAINED IN UNHYDROGENATED IN SITU DOPED FILMS -STUDY OF DENSITY OF TRAPS-

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Low temperature unhydrogenated in situ doped polysilicon thin film transistors with a APCVD SiO_2 deposited gate insulator were fabricated. The polysilicon layers which make up the active layer and the in situ doped source and drain region were deposited, after an optimization of the deposition pressure step, in the amorphous state and crystallized by thermal annealing.

To obtain a good APCVD SiO_2 gate insulator / active layer interface quality, an oxygen Plasma + RCA-type wet cleaning were used.

These TFTs exhibit good electrical properties : a low threshold voltage (2V), a high field effect mobility (> 60 $cm^2.V.s^{-1}$) and a high On/Off state current ratio (> 10^7) in the linear mode.

It is worth noting that the hydrogen passivation was not performed, and the above lectrical performances are similar to those obtained on the hydrogenated TFTs. These high performances could be correleted to the low states density of traps at intergranular boundaries and/or at SiO_2 gate insulator / active layer interface.

FORMATION OF n-p JUNCTIONS IN p-TYPE MBE HgCdTe FILMS BY LOW-TEMPERATURE ELECTRICAL ACTIVATION OF IMLANTED BORON ATOMS

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The use of boron ion implantation for obtaining p-n junctions in p-type $Hg_xCd_{1-x}Te$ (MCT) is of increasing interest because boron is a donor in this compound semiconductor. Heterostructures HgCdTe/CdTe/GaAs grown by molecular beam epitaxy (MBE) were used for the formation of n-p junctions due to the low-temperature electrical activation of implanted boron atoms. Growth of MCT layers was carried out by using an "Obj" MBE system.

The initial composition at the MCT film/buffer layer interface was x_{CdTe}=0.3. Then, it changed to x_{CdTe}=0.225±0.005 in the active layer. The active layer thickness was 9 μm. On the MCT film surface the composition increased up to x_{CdTe}=0.40 The thickness of wide bandgap layer was 0.35 μm.

MBE growth gave the n-type material. The annealing of the n-type MCT films at temperature 210 ^{0}C during 120 h in inert gas atmosphere resulted in the p-type material with hole concentration $p=(6\text{-}9)\times10^{15}$ cm^{-3} and mobility μ_p= 500-600 cm^{2}V$^{-1}\cdot$s^{-1}.

The p-type MBE MCT films were implanted at room temperature with 350 keV B^+ ions up to a dose of 1×10^{15} cm^{-2} through an anodic oxide with a thickness of 100 nm. The same control samples were implanted with N^+ ions under analogous conditions. The double implantation of B^+ and N^+ ions was carried out, too.

The two-step post-implant annealing under an anodic oxide was carried out at 250 °C for 2 h and then at 200 °C for 22 h in a nitrogen atmosphere.

Differential Hall effect measurements at 77 K with mobility spectrum + multi-carrier fitting analysis, optical reflection and secondary ion mass spectroscopy were used for implanted surface layer studies.

Mercury loss was found not to occur from the surface of MBE MCT films through an anodic oxide cap during such heat treatment.

The doping efficiency of boron atoms achieves 20% and it decreases with the increasing boron ion dose. The effect of boron electrical activity increasing during a temperature cycling by cooling up to 77 K and then heating to room temperature was detected for the first time. It was established that implanted nitrogen is a very active acceptor impurity.

Photosensitive n-p junctions in the p-type MBE MCT were formed by boron ion implantation in the photoresist windows through an anodic oxide without an annealing and with a low-temperature activation annealing under an anodic oxide.

The MCT-dielectric interface was prepared by CVD deposition of a low-temperature silicon dioxide at reduced pressure in the process of monosilane oxidation with oxygen in argon flux at T=100 ^{0}C without additional activation. The interface was then passivated trough deposition of PECVD silicon nitride during chemical reaction between monosilane and ammonia running in glow discharge plasma at 50 ^{0}C.

The 128×128 photodetector arrays with 50 μm pitch and 25×25 μm n-p junction were manufactured by planar technology using low-temperature photolithography with thermal treatment of photoresist layers at $T < 100$ ^{0}C.

The major photoelectric characteristics - dark- and photo-current, differential resistance of the photodiodes were measured in a nitrogen cryostat. It was established that boron activated n-p junctions have more better characteristics than one formed without annealing.

DIFFERENTIAL MAGNETORESISTANCE METHOD FOR THE CHARACTERIZATION OF ELECTRON AND LIGHT-HOLE CONCENTRATIONS AND MOBILITIES IN NARROW-GAP p-TYPE HgCdTe

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A simple direct characterization method based on differential magnetoresistence (DMR) measurements has been developed to determine the concentrations n, p_l (conductivities σ_n, σ_l) and mobilities μ_n, μ_l of the electrons and light holes, respectively in the narrow-gap p-type $Hg_{1-x}Cd_xTe$ (x~0.20) (MCT). The technique comprises simultaneous measurements of the magnetoresistance $\beta(B)=(\sigma_0-\sigma(B))/\sigma(B)$ and differential magnetoresistance $d\beta(B)/dB$. Magnetic field dependent Hall coefficient $R_H(B)$ indicates the presence of electrons in the p-type MCT if mixed-conduction regime takes place. In this case the differential magnetoresistance has two maxima. The first one at $B=B_1$ is determined by the electrons and the second one at $B=B_2$ is due to the presence of light holes. The magnetoresistance has values β_1 at a magnetic field B_1 and β_2 at B_2. The parameters μ_n, μ_l, σ_n and σ_l can be determined from the simple relationships (1) and (2):

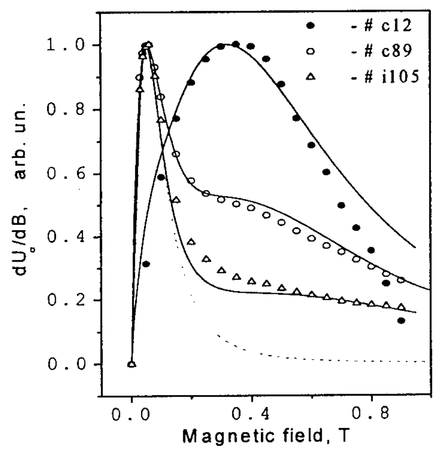

Fig.1. Signal dU_σ/dB vs. a magnetic field at 77K.

$$\mu_l=1/(B_2\sqrt{3}),\quad \mu_n=1/(B_1\sqrt{3})+\mu_l. \qquad (1)$$

$$\sigma_n = (x_1y_2 - x_2y_1)/(z_1y_2 - z_2y_1),$$
$$\sigma_l = (x_1z_2 - x_2z_1)/(y_1z_2 - y_2z_1),$$
$$x_i = \sigma_0\beta_i[1+(\mu_n^2+\mu_l^2)B_i^2+\mu_n^2\mu_l^2B_i^4],$$
$$y_i = (1 + 2\beta_i + \mu_n^2B_i^2)\mu_l^2B_i^2,$$
$$z_i = (1 + 2\beta_i + \mu_l^2B_i^2)\mu_n^2B_i^2,\ i=1,2. \qquad (2)$$

If one peak is observed at $B=B_j$ concerned only with electrons ($j=n$) or light holes ($j=l$) the carrier mobility can be derived from Eqs. (1) and conductivity can be obtained from the relationship ($\beta_j=\beta(B_j)$)

$$\sigma_j = \frac{\beta_j\sigma_o\left(1+\mu_j^2B_j^2\right)}{\left(1+2\beta_j\right)\mu_j^2B_j^2},\ j=n,\ p_l. \qquad (3)$$

The differential magnetoresistance $d\beta(B)/dB$ can experimentally be measured if a constant magnetic field is modulated by a weak magnetic field. The modulation is created by a solenoid located near a sample. The magnetic field variable signal dU_σ/dB is filed by the synchronous detector on a modulation frequency. Fig. 1 illustrates the dependence of dU_σ/dB versus magnetic field for three p-type MCT samples with various x values at 77 K. For a comparison the samples were analyzed by more composite mobility spectrum (MS) + multi-carrier fitting (MCF) procedure. The solid lines indicate the derivatives calculated from the results of MS+MCF analysis. The dashed line shows the theoretical derivative for the sample #c89 due to the contribution of electrons. The results obtained by DMR and MS+MCF methods are given in Table 1. The Eqs. (1)-(3) were used for the DMR method.

Table 1. Concentrations n, p_l and mobilities μ_n, μ_l of the electrons and light holes at 77 K

Sample	# c12 (x=0.220)		# c89 (x=0.205)		#i105 (x=0.200)	
Method	MS+MCF	DMR	MS+MCF	DMR	MS+MCF	DMR
μ_n, cm^{2}V^{-1}c^{-1}	90000	-	107000	111000	110000	115000
μ_l, cm^{2}V^{-1}c^{-1}	18000	17000	15000	15000	11000	-
n, cm^{-3}	$2.9\cdot10^{10}$	-	$1.7\cdot10^{11}$	$1.5\cdot10^{11}$	$1.7\cdot10^{12}$	$2.2\cdot10^{12}$
p_l, cm^{-3}	$3.4\cdot10^{12}$	$4.0\cdot10^{12}$	$4.6\cdot10^{12}$	$4.0\cdot10^{12}$	$3.7\cdot10^{13}$	-

It is clear from Fig. 1 that the light holes and electrons are available in the sample #i105 and sample #c12, respectively. However for the more precise definition of a maxima position it is necessary to measure a flexon d^2U_σ/dB^2. This technique will be developed.

THE EFFECT OF AN INTERFACIAL LAYER ON THE RELAXATION OF CDMNTE/CDTE MULTIPLE QUANTUM WELL STRUCTURES ON INSB SUBSTRATES

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CdMnTe/CdTe multiple quantum well structures on InSb substrates have been investigated by means of high-resolution x-ray diffraction and topography. Simulation of the high resolution x-ray diffraction profiles provided evidence of an interfacial layer at the interface between the InSb substrate and CdTe buffer layer. The topographs reveal the presence of misfit dislocations only in the sample with a thicker interfacial layer. We show theoretically that an In_2Te_3 interfacial layer will significantly affect the critical thickness for misfit dislocation generation. We confirm experimentally that only the sample with the thicker interface layer exceeds the critical thickness.

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Poster Session B

Tuesday, 4.00 p.m – 5.00 p.m

Growth of Tl-Containing Compounds by Gas Source Molecular Beam Epitaxy

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$III_{1-x}Tl_xV$ compounds have been proposed as potential IR materials[1-3]. In addition to the desirable bandgaps which have been predicted for these alloys, (1.35 eV to -0.27 eV for X_{Tl} of 0 - 1 in $In_{1-x}Tl_xP$ for example), the lattice constants are expected to differ from those of commercially available III-V substrates by less than 2%, thus allowing the use of III-V substrates [1]. Because of this potential, the conditions needed to produce Tl-containing alloys, and the composition and structure of the Tl-V binaries have been investigated, using elemental Group III sources and catalytically decomposed PH_3 or AsH_3 or elemental Sb in a gas-source molecular beam epitaxy (GSMBE) system. For both TlP and TlAs, metallic Tl was found to be the dominant phase for growth temperatures above ~300°C, with no evidence of the formation of any Tl-V phase. By reducing the temperature to 225-275°C, an As containing Tl phase was obtained. Calculations using the SRI model suggest that the difficulty in forming the P and As containing binary alloys is due to the high group V vapor pressures expected above these compounds. By contrast, Tl was found to react much more readily with antimony allowing a Tl-Sb phase to be obtained at much higher temperatures (400°C). For all of the binary materials it was found that the equilibrium binary phases do not have a 1:1 (Tl:V) stoichiometry. For the $TlAs_x$, the ratio appears to be roughly 3.5:1 Tl:As. Evidence of Tl metal can also be seen in electron microprobe analysis (EPMA) of the surfaces. Somewhat different behavior is obtained with Sb in the presence of Tl, in that no evidence of Tl metal can be observed. The deposited material is found to be Sb_2Tl_7 and elemental Sb, with the Sb_2Tl_7 taking the form of a shell around the Sb droplet.

Attempts to synthesize the ternary alloys containing In and Tl have under most conditions produced mixtures of the InV binaries and the TlVx binaries described above or elemental Tl. For InTlP deposition at temperatures above 375°C, the Tl simply evaporates from the surface, while at lower temperatures the Tl floats atop the surface leaving defective InP underneath metallic Tl droplets. For InTlAs, growth temperatures of 325°C or higher produced the same result as for the phosphide. By growing at low temperatures, InTlAs was obtained, however, along with elemental Tl. Under no conditions was a ternary InTlSb alloy obtained. Similar desorption behavior was observed for GaTlAs, however, it was possible to form a single phase containing Ga, Tl and As at low deposition temperatures. Unlike the other Tl-containing samples, this material is air stable. The GaTlAs is found to be As-rich, highly resisitive and amorphous.

1. A. Sher and M. Van Schilfgaarde, Appl. Phys. Lett. 1994.
2. M. Razeghi, presented at the Fall Meeting of the Electrochemical Society, Miami, FL, 1994.
3. H. Asahi, presented at the Int. Conf. on Molecular Beam Epitaxy, Malibu, CA, Aug. 1996.

Non-alloyed ohmic contacts using MOCVD grown $In_xGa_{1-x}As$ on n-GaAs

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Abstract: An important requirement for all types of semiconductor devices are low resistance ohmic contacts. Due to pinning of the surface Fermi level at mid band-gap, the metal-semiconductor (MS) barrier height for n-GaAs is typically 0.8-0.9eV. Since the maximum bulk doping concentration for n-type GaAs is limited to less than $1\text{x}10^{19}\text{cm}^{-3}$, contact alloying is employed to dope the surface of the cap layer to achieve a low contact resistance (see Fig. 1a). However, alloying is undesirable since it causes poor surface morphology, loss of edge definition and lack of uniformity, making such contacts unsuitable for small geometry GaAs-based devices. $In_xGa_{1-x}As$ cap layers can provide low resistance non-alloyed ohmic contacts due to lower MS barrier heights and higher attainable electron doping concentrations. Nevertheless, a large conduction band offset exists, approximately 60% of ΔE_G, at the InGaAs/GaAs heterojunction interface (see Fig. 1b), thus the need to compositionally grade the heterojunction. Furthermore, growth parameters are critical, not only to form smooth graded regions and high doping, but also to obtain smooth surface morphology.

In this work, TLM structures were fabricated using MOCVD grown, Si-doped In_xGa_xAs (N_D>$1\text{x}10^{19}\text{cm}^{-3}$) cap layers using different growth conditions, mole fractions and gradings. End contact resistance TLM measurements were carried out on these samples using the Ni/AuGe/Ni/Au and Ti/Au metallisation systems. The best results were obtained for graded $In_{0.5}Ga_{0.5}As$ layers doped $N_D\approx1.8\text{x}10^{19}\text{cm}^{-3}$ for which a specific contact resistance, $\rho_c=2.5\text{x}10^{-7}\Omega\text{cm}^2$ was measured. In order to verify these data we developed a theoretical model. In this model, the specific contact resistance, ρ_C, which is defined as resistance at zero bias, can be expressed for a metal-semiconductor junction as (symbols have their usual meanings):

$$\frac{1}{\rho_C}=\frac{4\pi q^2 m_n}{h^3}\int_0^\infty \frac{T(E)}{1+\exp\left[\left(E-E_F\right)/k_BT\right]} \qquad T(E)=\begin{cases} 2i\int_{x_1}^{x_2} -i\sqrt{\dfrac{8\pi^2 m_n q}{h^2E_G}\left[\psi(x)-E\right]\left[E_G+E-\psi(x)\right]}\,dx & \text{for } 0<E<\phi_{bn} \\ 1 & \text{for } \quad E>\phi_{bn} \end{cases}$$

where T(E) is the tunnelling probability using the WKB approximation; E is energy of the electrons in the x-direction from the bottom of the conduction band with x_1 and x_2 the corresponding turning points; and $\psi(x)$ is the parabolic potential including image force effects. It can be seen from the simulated data shown in Fig. 2, that for a doping of $1.8\text{x}10^{19}\text{cm}^{-3}$, a specific contact resistance, $\rho_c=3.5\text{x}10^{-7}\Omega\text{cm}^2$ is predicted, which compares well with the measured result. This model is being enhanced to include other barrier lowering effects.

The different growth variations and the reliability of these InGaAs contacts will be discussed and compared to GaAs contacts. An ohmic contact system using a novel refractory metal, zirconium diboride, will be also presented.

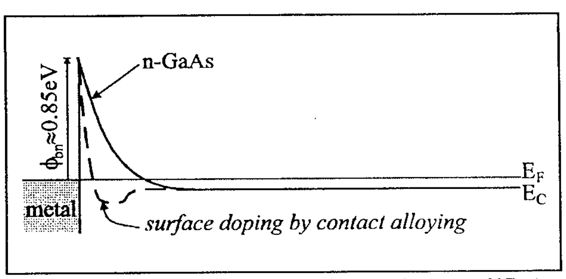

Fig. 1a: Schematic band diagram of a metal/GaAs contact before and after contact alloying

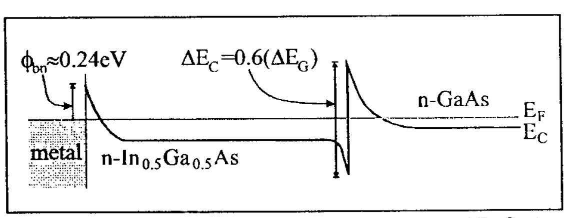

Fig. 1b: Schematic band diagram of a metal/InGaAs contact and InGaAs/GaAs heterojunction

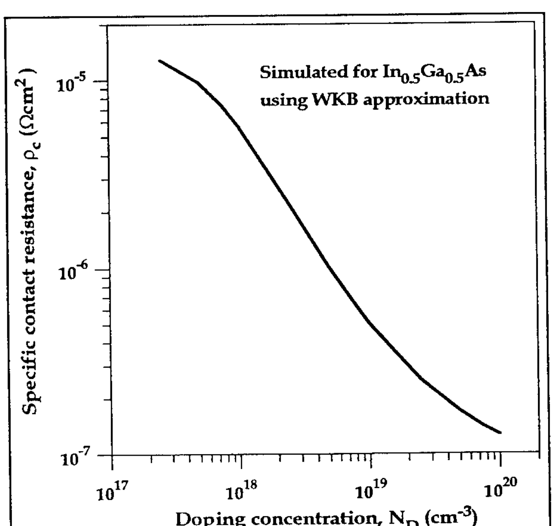

Fig. 2: Modelled specific contact resistance as a function of doping concentration for $In_{0.5}Ga_{0.5}As$ ohmic contacts

PROCESS OPTIMISATION OF THE REACTIVE ION ETCHING OF GALLIUM NITRIDE IN METHYLCHLORIDE/HYDROGEN USING THE ORTHOGONAL DESIGN METHOD.

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Cardiff School of Engineering
University of Wales Cardiff

ABSTRACT

We report the use of the orthogonal design method to optimise the reactive ion etching of Gallium Nitride (GaN) using MethylChloride/Hydrogen, CH_3Cl/H_2. This is the first report of the reactive ion etching of GaN using CH_3Cl/H_2 and etch rates of 110 nm/min have been obtained with a total flow rate of 50 sccm, a pressure of 35 mTorr and a plasma power of 350 W . The effect of the R.F. power input, total gas flow rate, pressure and the gas chemistry on the etch rate were investigated. The orthogonal design method allowed the effect of various parameters to be investigated and the optimum process to be identified.

There has been much recent interest in Gallium Nitride for both electronic and optoelectronic applications. The wide band gap of GaN allows it to be used to produce LED's, lasers and photodetectors in the shorter wavelength visible spectrum while the chemical stability of GaN enables it to be used to produce transistors that can handle high power levels and operate at temperatures approaching 500 °C. The high bond strength associated with GaN makes it hard to process and very resistant to wet chemical etching. The lack of a suitable wet etch for processing has resulted in much interest in developing dry etch processes suitable for the production of transistors and lasers.

The GaN films used in the development of this process were grown by Metal Organic Chemical Vapour Deposition (MOCVD). The etch mask on all samples was formed by depositing SiO_2 by Plasma Enhanced Chemical Vapour Deposition, PECVD and patterned using photolithography and etching in a 10:1 buffered HF solution. The plasma reactor used in all experiments was an Oxford Plasma Tech RIE80 system. A RF plasma was generated using a 13.56 MHz power supply. The samples were mounted on a quartz cover plate with a graphite surface. Etch rates were calculated by measuring the depth of the etched features with a Dektak stylus profilometer before and after the SiO_2 film was removed. This allowed the selectivity between then GaN and the SiO_2 film to be calculated.

The orthogonal design method allows the study of one of the parameters affecting the etch rate in isolation of all others. The parameter of interest is kept constant while several process runs are carried out while the other parameters are varied. The average etch rate of these runs is then taken as the value for that parameter setting. This parameter is then changed and more runs performed to obtain the average rate at this new setting. Using this method the process dependency of the individual parameters was discovered.

The etch rate for GaN as a function of RF power with all other parameters held constant is shown in figure 1. The variation in etch rate and dc bias as a function of pressure, gas ratio and total flow rate have also been calculated. The selectivity between the SiO_2 and the GaN varied from approximately 5:1 to 2:1. The surface roughness was measured before and after etching with an AFM and no discernible difference was observed.

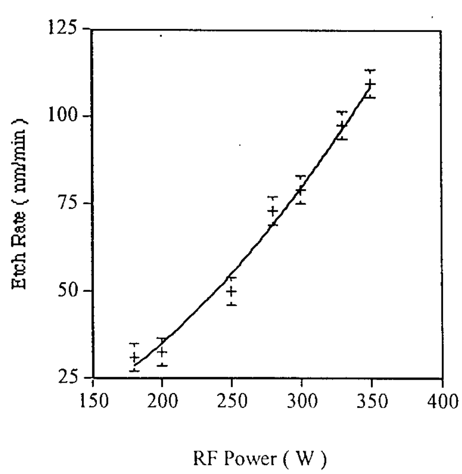

Figure 1. GaN etch rate Vs. RF power.

SEM AND AFM CHARACTERISATION OF HIGH-MESA PATTERNED GaAs AND InP SUBSTRATES PREPARED BY WET-ETCHING

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Patterning semiconductor substrates and their epitaxial overgrowth have become a subject of intensive research. This technology provides the possibility to form additional lateral confinement to the confinement which is created by the growth of thin semiconductor layers. Using this technology, a large number of quantum structures, mainly quantum wires (QWR) and quantum dots (QD), have been developed for use in lasers and other optoelectronic and electronic devices [1]. Although QWRs and QDs seem to have become the mainstream in this research, patterned substrates and epitaxial overgrowth have also been used for the development of other novel semiconductor structures. This was, for instance, demonstrated on manufacturing lateral p-n junctions on faceted substrates [2]. The prerequisite for successful use of this technology is good morphological quality of patterned substrates [3], [4].

In this work we have focused on characterising the morphological quality of etched surfaces produced by deep-mesa (40-50 μm) wet-etch-patterning of GaAs and InP semi-insulating substrates. (100) epi-ready GaAs and InP substrates, as well as InGaAs/InP and InGaP/GaAs semiconductor structures grown by MO CVD have been employed.

The substrates and structures were masked using positive photoresist AZ5214-E and they were etched through the photoresist, and through InGaAs and InGaP cap layers. Etchants based on H_2SO_4, H_3PO_4, HF, HCl, and citric acid have been tested with the aim to achieve smooth (100) surfaces as well as smooth mesa facets. The smoothness and morphological quality of etched surfaces have been characterised using scanning electron and atomic force microscopy techniques.

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THE USE OF CAPACITANCE-VOLTAGE (C-V) PROFILING TO INVESTIGATE THE HIGH FIELD, ELECTRON CAPTURE CHARACTERISTICS OF THE EL2 CENTRE IN GaAs

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Abstract

The EL2 Centre which occurs in semi-insulating (SI) GaAs grown form the melt is the key defect for ensuring repodocible and stable electrical properties of this important substrate material.

EL2 is a deep donor which under an applied electric field can exhibit strange behaviour where it fails to ionize and appears to be practically inert. This effect has been observed in many such devices such as nuclear particle detectors where a high applied electric field has been shown NOT to ionize those EL2 centres which were already present as neutral species and which were not involved in the initial compensation of the material. Such an effect may be due either to a dramatic reduction in its ionization rate or a similarly great increase in its electron capture cross-section.

In this work, we present C-V plots from low carrier concentration Te-doped n-type GaAs grown by the Liquid Czochralski (LEC) method. Such material has a carrier concentration of $\sim 10^{15}$ cm^{-3} but an EL2 concentration of $\sim 10^{16}$ cm-3. The capacitance-Voltage behaviour of Schottky diodes fabricated on this material are analyzed using the traditional "dopant profiling" technique. The results are found to be consistent with an abrupt depletion model in which a modification by field enhanced recapture of electrons by the EL2 centres occurs.

Study of Silicon doped VGF-GaAs by DSL-Etching and LVM Spectroscopy

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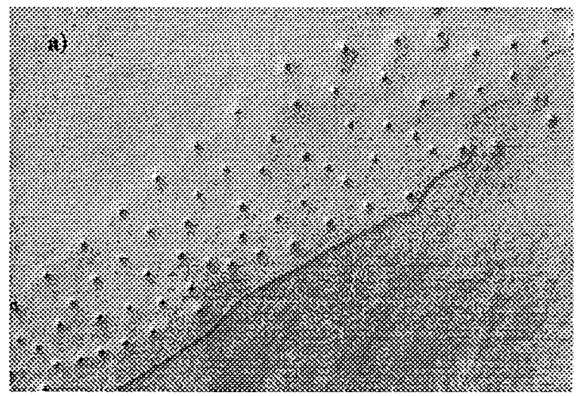
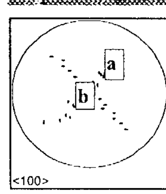
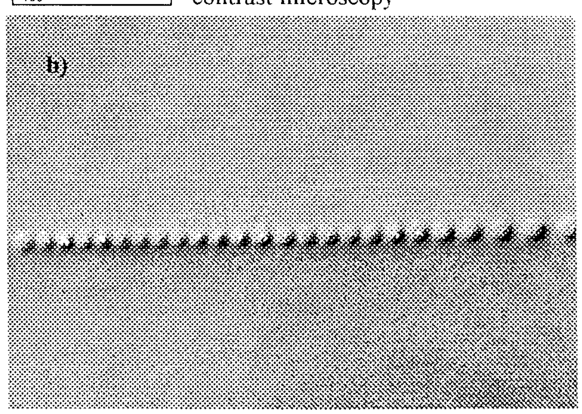
Silicon-doped <100> oriented GaAs crystals with free carrier concentrations between $2 \cdot 10^{17}$ and $3 \cdot 10^{18}$ cm^{-3} were grown succesfully with and without B_2O_3-coating using the vertical Gradient-Freeze-Method [1]. Growth experiments with full encapsulation (FE - VGF) of the GaAs resulted in dislocation densities (EPD) lower than 200 cm^{-2} with an X-shaped configuration of the etch pits in all investigated crystal wafers.

A X-shaped arrangement of these dislocations in <100> wafer direction was also observed at the lower carrier concentrations. This four-fold symmetric configuration shows that the generation of dislocations from the periphery of the ingot could be supressed by an optimized thermal process and an additional liquid B_2O_3 layer. Investigations of the resulting dislocation distribution by molten KOH and DSL etching showed that there are nearly dislocation-free regions between the <100> crystallographic directions of all investigated wafers. Structural results demonstrated that the main part of residual dislocations developed from the seed. The arrangement of grown-in dislocations in the (001) wafer plane can be explained by the symmetric axial temperature distribution in the melt and the propagation of dislocations perpendicular to the solid-liquid interface in the crystal seed. These results were confirmed in different growth experiments using LEC-GaAs (EPD $\approx 10^5$ cm^{-2}) as seeding material. The four-fold dislocation arrangement was observed only in Si-doped low EPD GaAs crystals grown with B_2O_3 encapsulation.





Arrangement of dislocations in <100> wafer direction (a) and center (b) after diluted Sirtl-like etching with the use of light (DSL) inspected by Nomarski interference contrast microscopy



Single crystals grown without additional encapsulation show that the free electron concentration n corresponds to the Silicon concentration in the melt. The application of B_2O_3 prevents the incorporation of Silicon and causes a reduction in the carrier concentration. Using SiAs it was possibile to obtain a higher concentration of n.

Local vibrational mode (LVM) spectroscopy has been used to study the incorporation of Silicon and Boron in different as-grown samples compensated by electron irradiation. In addition to the LVM lines of Silicon impurities the modes of B_{Ga}, B_{As} and Si_{Ga}-B_{As} were observed in crystals grown with full encapsulation.

The concentration of B_{Ga} in the range of 10^{18} cm^{-3} seems to be responsible for the dislocation reduction in crystals with low carrier concentration. The low EPD could be caused by impurity hardening because of the stronger lattice contraction of the FE-VGF GaAs [2].

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/2/ I. C. Bassignana, D.A. Macquistan, G. C. Hillier, R. Streater, D. Beckett, A. Majeed, C. Miner, Journal of Crystal Growth 178 (1997) 445

GROWTH OF Hg1-x(Cd1-yZny)xTe EPILAYERS ON (100) Cd1-yZnyTe/GaAs SUBSTRATES BY ISOVPE

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Hg1-xCdxTe (MCT) is currently used for infrared detectors. The lack of availability of large area substrate and the lattice mismatch of MCT-CdTe is generally recognized as a main limitation on efficient MCT detector technology. In order to solve these problems, the CdZnTe epilayers grown on GaAs have received much interest as a substrate material. On the other hand, MCT has a number of fundamental and technological problems caused by the weak Hg-Te bond on alloy with CdTe. For this reason, Hg1-x(Cd1-yZny)xTe (MCZT) has been proposed as the possible replacement for MCT.

Since the isothermal vapor phase epitaxy (ISOVPE) method is based on evaporation(interdiffusion mechanism, ISOVPE growth of MCZT possesses the advantage that the grown epilayers can be lattice matched to CdZnTe substrates with a proper composition value. This indicates that the MCZT epilayers grown using lattice matched CdZnTe substrate improve possibly the structural properties of epilayer.

In the present paper, the MCT and MCZT epilayers were grown by ISOVPE using CdTe and Cd1-yZnyTe (y = 0.045, CZT) layers, respectively, of various thickness on (100) GaAs as substrates. The effect of the thickness of substrate layers on their structural properties is discussed. Compared to MCT/CdTe/GaAs, the quality improvement of MCZT/CZT/GaAs is also reported.

(100) CdTe and CZT (y = 0.045) substrate layers were grown on (100) GaAs using hot wall epitaxy method with a Cd reservoir and subjected to the substrates for ISOVPE growth of MCT and MCZT, respectively. The growth of MCT and MCZT epilayers was performed in a semiclosed open-tube ISOVPE apparatus using HgTe source prepared by sublimation method. ISOVPE growth was carried out at 773 K for 3 h. Morphology and film thickness from cleaved cross-sections were examined by SEM observation. EPMA was employed to determine the composition of epilayers. The crystalline quality of epilayers was determined by four crystal X(ray rocking curve measurements.

At the interface between substrate layer (CdTe and CZT) and GaAs, the formation of triangular voids was found, after ISOVPE growth of MCT and MCZT epilayers, which depends strongly on the thickness of the substrate layers. The problem of void formation and Ga outdiffusion can be overcome by using a sufficiently thick substrate layer.

For the CdTe layers grown on GaAs substrates, the FWHM value of 90 arcsec is obtained at the thickness over 10 (m. The FWHM of CZT epilayers is 150 arcsec which is larger than that of CdTe. This is a characteristic of CZT grown by VPE technique and is attributed to phase separation. The ISOVPE MCT and MCZT epilayers grown on the thicker substrate than 2 (m show a FWHM value independent of the quality of substrate layer. MCT epilayers grown on CdTe/GaAs substrates have FWHM values in the range of 100 - 125 arcsec. It should be noted, on the other hand, that FWHM values for MCZT epilayers grown on lattice matched CZT/GaAs substrates are 75 to 90 arcsec smaller than that of MCT/CdTe/GaAs. Despite the broader FWHM for CZT/GaAs, an improvement in the FWHM of ISOVPE MCZT epilayers grown on these substrates is found.

Ion Implantation Induced Defects in SI Implanted GaAs Studied by Variable Energy Positrons.

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P.G. Coleman

School of Physics, University of East Anglia, Norwich, NR2 7TJ.

Positron annihilation spectroscopy (PAS) is a relatively new technique for probing defects induced by implantation. It allows the distribution and concentration of vacancy-related defects to be studied to a sensitivity limit of 10^15cm-3. The technique is described, together with a study of defects induced by the implantation of 120 keV Si+ into SI-GaAs for doses ranging from 10^11-10^14cm-2. Application of the technique to the study of implant isolation and carrier activation in GaAs is also discussed.

PHOTOEMISSION AND RAMAN STUDY OF GaAs PASSIVATED IN ALCOHOLIC SULFIDE SOLUTIONS

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Stefan Hohenecker and Dietrich R.T. Zahn
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D-09107 Chemnitz, Germany

Sulfidization of GaAs in alcoholic solutions is a promising technique for modification of the surface electronic properties [1]. It was recently shown that such treatment of InGaAs/AlGaAs SQW lasers increases the catastrophic optical damage limit and the slope efficiency [2]. In this paper we have studied electronic properties and chemical composition of the surface of n- and p-GaAs treated in different alcoholic sulfide solutions.

The investigations were performed on wafers of GaAs:Te(100) with $N_D=1x10^{18}$ cm^{-3} and on GaAs:Zn with $N_A=2x10^{18}$ cm^{-3}. The sulfide treatment was carried out in the following solutions: a) solutions of ammonium sulfide in water, isopropanol, and tert-butanol; b) solutions of sodium sulfide in water, isopropanol, and tert-butanol.

By XPS it has been shown that after passivation in any solution the thickness of oxide layer is decreased while As-S and Ga-S bonds are appeared on the surface.

By micro-Raman the depletion layer of passivated GaAs was investigated using experimentally determined ratio of the intensities of LO phonon peak and L^- phonon-plasmon mode peak. It has been shown that the depletion layer does not change after passivation in aqueous solutions of sodium sulfide and ammonium sulfide while after passivation in alcoholic solutions the considerable reduction (approx. 2 times) of the depletion layer has been observed both for n-GaAs and for p-GaAs. Such reduced depletion layer remains unchanged during the exposure in atmosphere within at least 2 months.

By photoemission the position of surface Fermi level for n-GaAs and p-GaAs, passivated in the solution of ammonium sulfide in isopropanol was determined. It has been found that the surface Fermi level is pinned in the position of 0.25 eV (for n-GaAs) and of 0.35 eV (for p-GaAs) below the bottom of the conduction band. That is the surface barrier is reduced for n-GaAs and increases for p-GaAs after passivation in this solution. To fulfill this data with micro-Raman results the conclusion about presence on the surface of the dipole layer should be made.

This work was supported in part by Grant from Volkswagen-Stiftung.

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INVESTIGATION OF MBE GROWN GaAs/AlGaAs/InGaAs HETROSTRUCTURES

R.Melkadze, N.Khuchua, Z.Chakhnakia, T.Makalatia, G.Peradze, T.Khelashvili

RPC "Electron Technology" under Tbilisi State University

The creation of very high-speed integrated circuits and high-efficiency solar cells resulted in the development of III-V heterostructures.

Technological investigations on production of $GaAs/Al_{0.25}Ga_{0.75}As/In_{0.1}Ga_{0.4}As$ and $GaAs/Al_{0.8}Ga_{0.2}As$ heterostructures using the MBL technique have been carried out.

Photoluminescence spectra with 2DEG as well as electrophysical parameters of heterostructures have been carried out by the noncontact method of RF magnetoresistance.

On the basis of the producd heterostructures the requency divider ICs and HEMT are obtained and their characteristics are presented.

The efficiency of p-n GaAs solar cells with the $GaAs/Al_{0.8}Ga_{0.2}As$ optical window is 15÷16% with the emitter and base layer concentration $\sim 1 \div 4 \cdot 10^{17} cm^{-3}$.

A new method of precision thinning of GaAs structures by dynamic chemical etching has been developed and studied. The etching rate is $8 \div 10 \mu m/min$.

THE MEASUREMENT OF SUBSTRATE TEMPERATURE IN MBE SYSTEM

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We developed the contactless method for measurement of substrate temperature in the range 100-250^{0}C at molecular beam epitaxy *in situ*. This method based on the measurement and comparing the orthogonal polarized components of thermal emittance from the substrate in wavelengths range 20-30μ. At this condition there is the optical free carriers absorption. So the substrate is not transparent at this wavelengths and the thermal emittance from the heater do not influence on measurement of substrate temperature. The thermal emittance radiation of mirror-like adsorbing surface is partially polarized and depends on optical constant **n, k** and angle between the surface substrate and the axis of observation θ. At fixed θ the difference between orthogonal component of polarized thermal emittance ($R=R_{\perp}-R_{\parallel}$) is a function of the optical constant **n**, **k** and sample temperature **T**. In temperature interval 100-250^{0}C R is approximated by linear dependence on temperature.

The thermal emittance of the substrate which was mounted inside the vacuum chamber was measured throughout the special window (window material is KRS-5) by pyrometer operated in wavelengths range 20-30 μ. The angle of observation $\theta = 65^0$ is optimal for maximum sensitivity of our pyrometer to temperatures variation and minimum sensitivity to θ variation near this fixed angle value.

The calibration experiments for determination of the dependencies of pyrometer voltage on the substrate temperature were carried out. The temperature interval was 100 ÷ 250^{0}C. The substrates material was GaAs and CdTe epitaxial films on GaAs substrate. The substrates were 2 inch in diameter and mounted on special holder Ga and In free. The temperature was measured by thermocouple which contacted to substrate holder. The calibration curve in the plane of pyrometer voltage-temperature coordinates is linear. It is observed a good agreement between theoretical and experimental values. The accuracy of temperature measurements is equal to 1 ^{0}C.

During the calibration experiments the ellipsometric parameters Δ and Ψ were measured too by automatic single wave ellipsometer. This parameters depend on temperature too.

We determined the time difference between the variation of thermocouple voltage, pyrometer voltage and Δ and Ψ parameters at variations of heater power. We found when the thermocouple voltage reaches the constant value the pyrometer voltage and the parameters of Δ and Ψ reach their constant values about 30 minutes later. Using our pyrometer now we can more accurate to determined the substrate temperature and its variation during the preparation MBE system to the growth. We used pyrometer for monitoring the temperature during the growth of HgCdTe heterostructures.

THE OPTICAL REFLECTANCE SPECTRAL METHOD FOR THE EVALUATION OF CRYSTAL QUALITY OF CdTe FILMS ON GaAs AND HgCdTe

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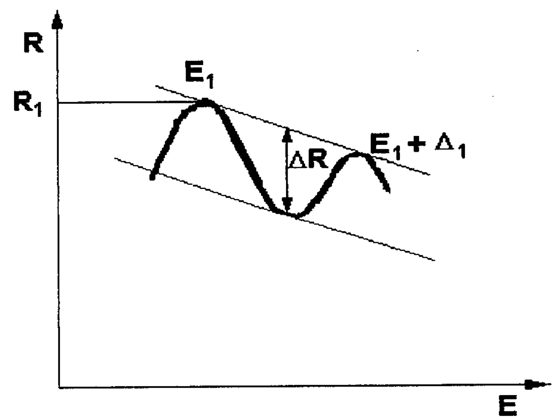
The use of the reflectance doublet peaks in visible range (E_1 и $E_1+\Delta_1$) for the evaluation of the crystal quality near the surface (the thickness is approximately 0.1 nm) has been suggested. This procedure was applied for the first time. The technique comprises the measurement of parameter $Q = \Delta R/R_1$ which corresponds to the reflection peak sharpness; where $\Delta R = E_1 - E_2$ and R_1 - absolute value of E_1 peak. (see Fig 1).



This research is devoted to the crystal quality of (100) CdTe films grown by MBE on (100) GaAs substrate in optimal growth conditions . The film thickness was from 2μm up to 7μm . The growth rate was about 1μm/h.. X-ray rocking curve and reflection spectra were measured. It was shown that the parameter Q increases with the increasing of film thickness. At the same time FWHM of rocking curve decrease which connected with the improving in crystal quality.

We use the parameter Q for the evaluation of crystal damages in HgCdTe ($X_{CdTe}=0.2 \div 0.3$) created by ion implantation of P^+,B^+, Ar^+, Kr^+, Xe^+ ions at an energy of $50 \div 135$кэВ and the dose of $10^{13} \div 10^{16}$ cm^{-2}. The crystal imperfection and the depth of damaged layer were determined from the measurements of parameter Q during layer by layer chemical etching. The parameter Q versus the ion energy and dose were studied. The results is in a good agreement with the literature data.

So the reflectance method allows us to evaluate the crystal quality near the surface over the large areas very quickly and without any perturbation.

PREPARATION AND CHARACTERIZATION OF *n*- AND *p*-TYPE YTTERBIUM DOPED InP EPITAXIAL LAYERS

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The InP semiconductor layers are widely used for the fabrication of different micro- and optoelecronic devices. Recently, much attention has been devoted to the influence of the presence of rare earth elements (REEs) during the growth process on properties of the resulting layers or crystals [1]. REEs are characterized by very strong affinity to oxygen and other group IV and VI elements present in the growth system.

In our study we pursued the effect of the ytterbium addition during the liquid phase epitaxial (LPE) growth on physical properties of InP thin layers. Series of InP layer samples were prepared by LPE from the melt containing 0 - 0.6 wt% of Yb. The growth process was carried out in a graphite sliding boat in high-purity hydrogen atmosphere. Layers were grown on (100)-oriented semiinsulating InP:Fe substrates in the temperature region 650-620 °C [2,3]. The samples were examined by following physical diagnostic methods: Hall effect measurements, C-V measurements on Hg-contact, and Rutherford backscattering spectrometry. Low temperature photoluminescence measurements were used for the estimation of Yb content inside the InP layers. Yb impurity in InP layer is incorporated as a cubic Yb^{3+} ($4f^{13}$) centre on In site and sharp luminescence lines arising from crystal field split $2F_{5/2}$-$2F_{7/2}$ inner-shell transitions have been observed. We have found by room temperature Hall measurements that the grown layers are of *n*- or *p*-type in dependence on the quantity of Yb in the melt. The preliminary results show that carrier concentration in the n-type as growh InP:Yb layers can be near $1.0 \times 10^{15} cm^{-3}$ with the mobility of 7500 cm^2/Vs.The stability of the carier concentration values was studied under temperature annealing procedure. On the basis of these results we discuss the possibility of preparation of *p-n* junctions in the InP layers doped directly by ytterbium as the material for preparation of electroluminescent radiation sources.

This work has been supported by the Grant Agency of the Czech Republic, project No 102/96/1238.

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COMPARATIVE INVESTIGATION OF MBE AND MOCVD PMHEMT STRUCTURES FOR HIGH FREQUENCY APPLICATIONS.

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ABSTRACT

Significant effort has been devoted in recent years to pseudomorphic HEMT structures for high frequency and high power applications. The main advantage of these structures is the better confinement of the 2DEG that increases the sheet carrier concentration in the quantum well and decreases the device noise figure. The type of the heterostructure employed, combined with uniformity of the device characteristics across the wafer and reproducibility, from wafer to wafer, are critical parameters for the fabrication of MMICs.

The aim of this work was to compare the uniformity of the DC, RF and power characteristics of single and double heterostructures, grown on 3 inch (001) S. I. GaAs substrates by MBE and MOCVD. It was also attempted to identify the possible mechanisms limiting the high frequency performance of these devices.

In order to improve the source-drain breakdown voltage, a portion of the AlGaAs donor layer was left undoped. The gate recess, of 1.0 μm and 0.7 μm lengths, was performed by RIE for improved uniformity. Cut-off frequency and maximum available frequency were extracted from small-signal RF characterisation up to 20GHz. Power measurements were performed in the range from 8GHz to 12GHz utilizing the Load-pull technique, in a class A operation.

Although double heterostructures exhibited inferior DC performance compared to that of the single heterostructures, their RF and power characteristics were superior. The lower values of RF characteristics in single heterostructrures is attributed , in addition to the well documented lower confinement of the 2DEG in the quantum well, to incomplete depletion of the donor layer from free carriers. For this reason the I_{dss} is more uniform in the case of single heterostructures. However all important DC, RF and power characteristics exhibit similar uniformities. For that reason, we conclude that double heterostructures, although harder to realize, exhibit similar uniformities with the single ones.

Effect of Thermal Annealing in Different Ambient on Photoelectrical Properties of Chemical -Deposited CdS Thin Films

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Cadmium sulphide (CdS) thin films were deposited on glass substrates using the chemical deposition technique. The films were thermally annealed for 1 hour at 300°C in different ambients: air, vacuum, argon.

The photoconductive measurements performed on as-deposited and annealed CdS films are correlated with traps levels investigation by Thermally Stimulated Currents(TSC) method.

It was observed that the trapping levels are quasi-continuously distributed in the forbidden band of the as-prepared CdS thin films.[1] The air annealing increases the concentration of the trapped carriers.[1] After vacuum or argon annealing it was observed the healing of the shallow levels and a considerable decreasing of the trap centres concentration. An annealing treatment is accompanied by undesirable changes in the film stoichiometry.[2] These experimental results were explained considering an oxygen chemisorbtion-desorption process.[3]

The modification of the trapped charge had influenced the spectral distribution of the photocurrent and the relaxation of photoconductive signal because the photoconductive process is controlled by the trapping-detrapping processes.

The highest I_{light}/I_{dark} ratio and the quicker photocurrent decay is observed for CdS thin films annealed in argon.

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EFFECT OF RARE EARTH ADDITION ON LIGUID PHASE EPITAXIAL InP AND GaInAsP SEMICONDUCTOR LAYERS

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Epitaxial layers and heterostructures on the basis of III-V semiconductor compounds are generally used for the fabrication of micro- and optoelectronic devices. The unavoidable impurities that arise in epitaxial layers from the growth components and ambient represent a considerable problem that could be challenged by using the rare-earth elements addition during the growth process [1]. It has been found that most of the RE ions do not probably incorporate into the epitaxial layer at the growth temperatures about 630 - 700°C, similar to those used in liquid phase epitaxy technique (LPE), but could be used to remove certain impurities from the growth melts and to reduce amount of defects in semiconductor materials.

In this contribution we studied the effect of RE elements (Ho, Er, Yb and Eu) addition during the LPE growth on the resulting structural, electrical and optical properties of InP and GaInAsP layers. Series of layer samples were prepared by LPE from the melts containing 0-0.5 wt% of RE elements. The samples were examined by different physical diagnostic methods. The density of dislocations was markedly reduced and dramatic impact of the RE admixture on the free-carrier and residual donor concentrations has been observed. The conduction type, free-carrier concentration and mobilities were determined by temperature dependent Hall effect. Low-temperature photoluminescence (PL) spectra has been measured for various levels of excitation power. The major manifestation of RE admixture to the melt is the pronounced narrowing of PL spectra and the corresponding appearance of fine features of the spectra, characteristic of pure material, low in defects. Sharp inner-shell transitions characteristic of Yb^{3+} center have been observed. The influence of the particular RE elements on the overall characteristics of semiconductor layers were compared.

The research was supported by the Grant Agency of the Czech Republic, project No 102/96/1238.

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NETWORKS OF GaAs QUANTUM WIRES: PREPARATION AND CHARACTERIZATION

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While quantum well structures are widely used for optoelectronic applications, the structures with lower dimension (quantum wires - 1D and quantum dots - 0D) appear to be more difficult to fabricate. Nevertheless several methods were proposed for the fabrication of 1D and 0D including a lithographic patterning of 2D structures and a self-organized growth process/1/.

Here we report an alternative approach for fabrication of arrays of quantum wires using patterning of GaAs through a mesoscopic self-organized mask.

The technological approach of self-organized growth of a mask is believed to be described in the frame of Benard-Marangoni effect due to chemical variations, i.e. self-organization patterning at the liquid - gaseous interface/2,3/. A permanent regular structure is fabricated in a thin layer of double- diffusive system of quickly evaporating solvent and a polymer after an initial perturbation of the surface by a vapor of small water droplets, which can undergo a phase transition to symmetry breaking ordered state/4/. A solution of nitrocellulose as the polymer in amil-acetate as the solvent is used. A network is easily removed from the surface of the water to a solid substrate as a mask for further patterning, structural and electrical investigations. We manufacture GaAs arrays of wires using Ar ion etching. As a routine we get networks with the size of hexagonal cells less than 500 nm. The thickness of bonds is about 50 nm.

Scanning electron microscopy and Auger electron spectroscopy investigations are presented. Electrical properties of GaAs arrays of wires have been tested.

The new method of fabrication of 2-D regular networks could be a subject of importance for fundamental physics and device applications of mesoscopic structures. We expect to observe quantum effects in the resistance of metal and semiconductor networks/5/, effects of pinning of electron orbits as in antidot arrays/6/, properties of 2-D photonic band gap structures/7/ and the whole range of new mesoscopic device applications.

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Supporting data for review considerations

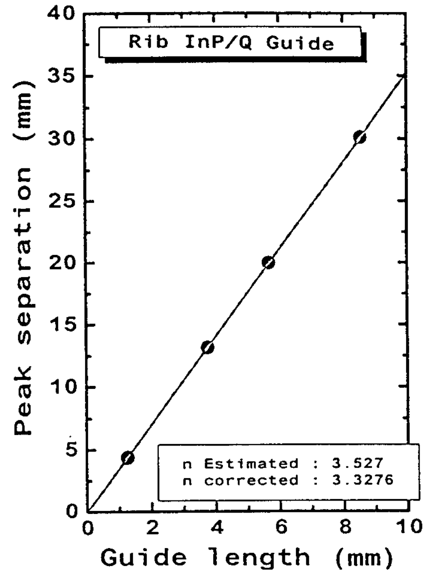

fig. 1

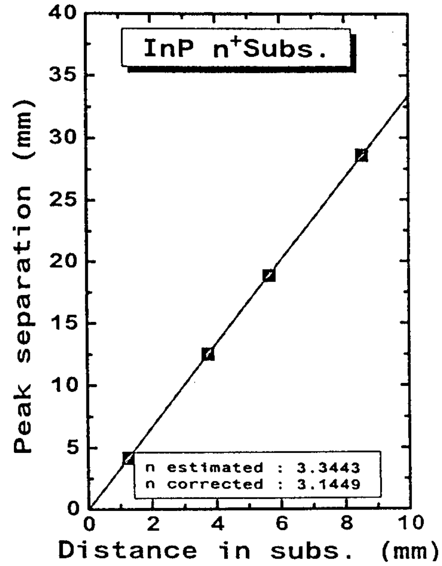

fig. 2

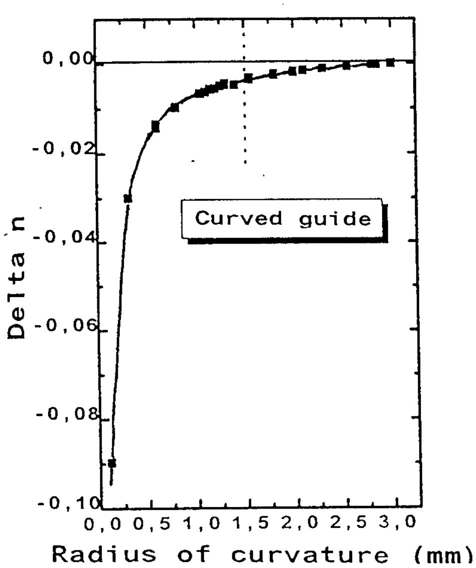

fig. 3

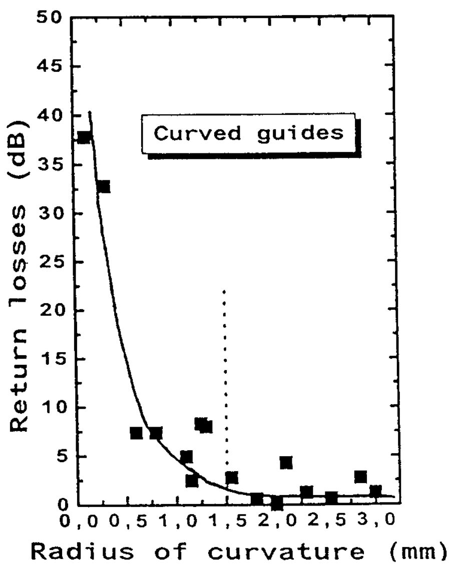

fig. 4

Figs. 1 and 2: Examples of the refractive index determination of the waveguide (fig. 1) and substrate (fig. 2) materials. Here the distance between two successive reflections is plotted against the distance traveled in the material.(Here, the correction is realized by measuring materials with known n values).

Figs. 3 and 4 : Examples of data recorded on curved guides. Here, Fig. 3 depicts refractive index difference (Δn) between curved and straight guides per unit curvature as a function of R_C.The greater the difference in Δn the smaller will be the light confinement in the curved guide. This shows that light severely radiates into the substrate beyond a R_C value of ~1.5 mm. Similarly, fig. 4 shows a strong increase in return losses also beyond ~1.5mm.

ISOPERIODICAL HETEROSTRUCTURES GaInAsSb/GaSb LPE-GROWN FROM Sb-RICH MELTS IN SPINODAL DECOMPOSITION AREA.

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Quaternary solid solutions $Ga_{1-x}In_xAs_ySb_{1-y}$ lattice matched to GaSb are very promising materials for mid-IR optoelectronics. Unfortunately, a wide solid phase miscibility gap and spinodal decomposition area inside the gap limit the possibilities of manufacturing of devices based on these solid solutions. The highest values of LPE-grown solid solutions obtained to date have been x=0.23, y=0.2 for solutions grown on GaSb (100) and x=0.26, y=0.23 for growth on GaSb (111) [1].

In this paper we report the LPE growth of $Ga_{1-x}In_xAs_ySb_{1-y}$ alloys lattice matched to GaSb from Sb-rich solutions. The reported solid solutions are inside the spinodal decomposition area (with maximum composition values x=0.4).

Epilayers have been grown from supercooled Sb-rich liquid phase at the constant growth temperature (570-600°C). The growth method has been described in [2]. We have obtained smooth surface epilayers grown on GaSb (100) and GaSb (111) B substrates. Growth rates in the area of spinodal decomposition were about 500 Å/min and layer thicknesses were limited between 200 and 2000 Å. The solid solution compositions were determined by secondary ion mass-spectroscopy (SIMS). The analysis of photoluminescence spectra and double-crystal X-ray diffractometry data allowed to determine growth conditions for both homogeneous solid solutions and alloys with spinodal decomposition attributes. For the formation of quantum size objects laser and thermal annealing of grown metastable quaternary epilayers was used.

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HYDROGEN PLASMA TREATMENT OF GERMANIUM DOPED n-GaAs

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Hydrogen, as a specific impurity, is well-known because of its impurity passivation effect also in the case of III-V semiconductors [1, 2]. Ge, as the element of the IV group, is known as an amphoteric impurity. In the case of vapour phase epitaxial methods, Ge is used, however, as an excellent donor. In spite of the intensive study of the impurity passivation effects by hydrogen diffusion, passivation of the Ge donor is not fully verified yet. In this work such type of experiments were carried out.

Highly doped n-type GaAs:Ge epitaxial layers have been grown both by chloride VPE and MOVPE methods on semi-insulating GaAs substrates. Galvanomagnetic properties, carrier concentration depth profiles and low temperature photoluminescence spectra were measured. GaAs:Ge samples underwent a hydrogen diffusion process in low pressure (~1 torr) and low temperature (<250 ^{o}C) radio-frequency induced hydrogen plasma. Two types of plasma treatments were applied. In one of them the epitaxial layer was placed directly into the plasma atmosphere between the metallic electrode plates. In the other case samples were placed outside of the volume determined by the electrode area in the direction of the vacuum pumping outlet (indirect plasma).

Same measurements were carried out on the same samples after the plasma treatment and the changes in the parameters were studied. In spite of a very strong donor passivation effect of the H in GaAs:Si described in the literature, the Ge passivation observed in these experiments indicate only a slight effect. Electron concentration depth profilometry and photoluminescence spectra indicated an effective donor passivation in the near surface region. The "efficiency" of the passivation was also different for the different plasma configurations.

Control samples were diffused using deuterium for SIMS depth profile measurements. Comparison of these depth profiles with the free electron depth distribution profiles indicate a near surface passivation activity. These figures exhibit a surface localised passivation possibility. This explains the limited efficiency of the passivation in general. Differences in the galvanomagnetic properties suggest that not only the impurities, but defects are also passivated by the hydrogen and the ratio of these effects can vary depending on the given properties of the sample.

This work was partly supported by Hungarian National Research Foundation (OTKA), grant No. T015619 and by the joint Hungarian-French "Balaton" project No. 35.

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SOME COMPARISON OF PROPERTIES OF THICK GaN LAYERS GROWN ON SAPPHIRE AND SILICON SUBSTRATES BY VPE

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Preparation and the study of GaN has recently a great new revival. The first revival, the attempts to grow different wide gap III-V-s, including also GaN crystals or layers did not lead to great success in seventies. New technologies, like MOCVD and MBE imparted very new possibilities and a real success to epitaxial growing of GaN, as well. In this work, however, GaN layers have been grown by the very first method, by the classical chloride transport vapour phase epitaxy [1-3]. This approach has great advantage of the high growth rate compared to the other methods. This method seems to be the only method capable for production of thick layers of sufficiently good quality, which can further serve as substrate material for homoepitaxial growth of GaN.

The most significant questions is the starting substrate material. Basically two types of substrates are used for GaN epitaxy: silicon and sapphire. In the case of use of silicon substrates, the lattice mismatching result in a wider interfacial layer with very high density of dislocations. Only thick layers, allowed e.g. by VPE, can have an upper region, which is a relatively good crystalline quality layer with good quality surface for further epitaxy. This fact stresses the importance of the application of VPE to growth of GaN.

Galvanomagnetic properties were measured in a temperature range between 77 K and room temperature. A usual DC setup was used with a magnetic field of about 0.35 T. A quasi static temperature regime was applied with slowly increasing temperature. For the electric measurements the sapphire substrate was the convenient, because of the dielectric character of the sapphire. In the case of silicon substrates the GaN layer was removed from the substrate by grinding and chemical etching of the substrate material. Because of the character of the interfacial layer between Si and GaN, the interfacial surface of the "lifted off" GaN layer remains/becomes rough. This roughness is sufficiently great to make difficulties in the thickness determination [4].

The results of galvanomagnetic measurements show a great similarity of the two types of layers. It is supposed that the observed elevated carrier concentrations are caused by nonstoichiometry, as it is usual for GaN layers obtained by various growth techniques. Specific influence of the different substrates is smeared under the consequences of the genuine properties of GaN.

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ENHANCEMENT OF THE PERFORMANCE OF GaAs PLANAR PHOTORESISTORS BY SULPHUR PASSIVATION OF THE SURFACE

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Undefined native oxide, charged states on the surface and the concomitant Fermi level pinning deteriorate the near surface electrical properties of the GaAs crystals [1, 2]. In combination with similar interfacial effects, this effect is extremely important in the case of thin epitaxial layers grown on semi-insulating substrates. Very different methods are used to avoid drawbacks of the phenomenon. Recently, exciting results have been achieved with the passivation influence of sulphur and other chalcogenides applied to the surface by several, mainly wet methods [3 to 5].

There are discussions concerning the mechanism of the reactions of these chalcogenides, however, the experiments show decrease in surface recombination velocity [6], an increase in the photoluminescence intensity [7] and transistor gain improvement, etc. In this paper we present some experimental results on the influence of sulphur passivation on the behaviour and the switching efficiency of GaAs planar photosensitive elements (PPE) by using $Na_2S x 9H_2O$.

Nearly semi-insulating epitaxial layers grown on semi-insulating substrates by the close spaced vapor transport technique were used for the preparation of the photoresistors. The thicknesses of the epitaxial layer were about 8.0 μm. The PPE structures studied were constituted by two rectangular ohmic contacts made on the top of the epitaxial layers with two different gaps between them (8.0 and 15.0 μm). DC I-V characteristics have been measured in dark and under illumination, and also a switching coefficient was calculated. For the illumination very low intensity light of an incandescent lamp was used. The estimated light power absorbed in the active part of the devices was below 0.1 mW.

The structures were cleaned in usual manner in degreasing solvents before the passivation. They were then lightly etched and after a light rinsing in deionised water they were dipped into a 1M water solution of $Na_2S x 9H_2O$ at room temperature, for about 10 s. After pulling out from the solution, the wafers have been dried under nitrogen stream.

I-V characteristics have been repeatedly measured for biases up to 10 V of both polarities. Typical example of dark I-V characteristics of as prepared and passivated samples are shown. The difference in characteristics under illumination and in dark is demonstrated. Results demonstrate the effect of the surface treatment on the surface states and surface conductivity processes: e.g. increase of the dark resistance of the samples.

Enhancement of the performance of photoresistive elements demonstrates the decrease of the surface recombination current, resulting in an increase of the light sensitivity and switching rate, as well. These results confirm the passivation of surface states through surface sulphur treatments. Further investigations with smaller layer thicknesses comparable with the light absorption depth are necessary. Also smaller gaps between the contacts and the changes in the speed of such devices are to be further studied.

The authors want to thank the CONACYT of México and the Hungarian Academy of Sciences for the support in the realization of this work. This work was supported a part also by the Hungarian National Research Foundation, OTKA grant No. TO15619.

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PRECISE MEASUREMENT OF THE TEMPERATURE DEPENDENCE OF THE HALL MOBILITY AT THE FIRST ORDER PHASE TRANSITION IN Ag_2Se LAYERS

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The temperature dependence of semiconductor parameters (resistivity, concentration and mobility of the charge carriers) has usually a "smooth" character without abrupt and significant changes of parameter values in a narrow temperature range. Great exceptions are the semiconductors changing their conductivity type at certain temperature (e.g. p-InSb at the transient to the intrinsic conductivity range, etc.) and some superionic or mixed conductivity ionic semiconductors undergoing first order phase transition at a critical temperature. In these cases also electrical properties exhibit sudden, drastic, "jerky movement" type changes, like it was sown e.g. in the case of Ag_2Se [1-3].

These changes are described also in the early literature as jump wise changes at a very distinct temperature of the polymorphic phase transition [4]. Temperature dependence of these transients of the galvanomagnetic properties obtained by Hall effect measurements can be measured with great difficulties, since the temperature window of the "jumps" is very narrow and, in contrast to this, each measurement lasts several minutes. According to the existing data this temperature window is less than 1 K. In this work we have measured first the full transient of the Hall effect (i.e. that of the concentration and of the mobility) with a very high resolution both in temperature and electrical parameters.

These measurements have been performed on mono- and polycrystalline Ag_2Se thin layers deposited and formed in vacuum on insulating NaCl substrates. Hall effect was measured by a conventional DC setup with usual conditions. The temperature range was between 77 K and 450 K, with a special attention to the temperature range at and around the polymorphic phase transition. Quasi static temperature conditions with continuos heating (or continuos cooling for the reverse process) were kept instead of a controlled temperature stabilisation. The asymptotic character of heating (and cooling) was exploited in order to reach a temperature resolution better than 0.1 K in measurements. Since the mentioned phase transition is reversible, the hysteresis of the phase transition and results both in heating and cooling regimes are presented.

Details of the method and its application are described. The main advantage of this asymptotic heating method compared to the conventional stabilisation method is that the temperature change is monotonous. The inertia of the sample holder assures that no oscillations occur even at levels of 0.01 K. Differentiating- integrating stabilisers do not allow such time consuming measurements with temperature differences 0.1 K. Temperature dependences of the mobility and the concentration of Ag_2Se layers show that the phase transformation is monotonous, in fact.

This work was partly supported by the Hungarian National Research Foundation, OTKA, contracts No.: TO4178, TO14110 and TO15619.

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THE STUDY OF SPECTRAL PHOTOCONDUCTIVITY RESPONCE OF MCT HETEROSTRUCTURES BY CONTACTLESS METHOD

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It is necessary to have the material of a large areas (about several square inches) for fabrication linear or matrix multielements IR-devices on the basis HgCdTe (MCT). The high requirements to uniformity of the physical characteristics and especially of MCT composition over the surface area are presented. It is necessary to have the uniformity of MCT composition (X_{CdTe}) with the accuracy $\Delta X_{CdTe} \leq 0.005$ that corresponds the uniformity of wavelength cut-off (λ_c) with the accuracy $\Delta\lambda_c \leq 1\mu$ for LWIR detectors (λ_c=12μ).

Usually MCT composition is determined by transmission optical spectra technique at room temperature. However these data do not always correspond to needed λ_c of IR-devices which operated at liquid nitrogen temperature. Moreover it is necessary to know the curve of spectral response at 77K which depends on MCT film thickness, MCT composition throughout the thickness, surface recombination velocity and etc.

We present the study of the spectral photoconductivity response (SPR) over the area MCT heterostructures (HS) by contactless microwave method at 77K. This method is based on the automatic microwave measuring at 38 GHz of transient photoconductivity excited by IR radiation from monochromator. The probe diameter is equal to 5 mm. This method allows to evaluate the absolute value of photoconductivity.

MCT HS were grown by MBE on 2 inch in diameter GaAs substrates. MCT HS composition X_{CdTe} =0.21 - 0.23. The accuracy of MCT composition over the surface areas was ± 0.006.

We compare the measured distribution of λ_c and the curve of SPR over the MCT HS surface areas with the MCT composition which was determined from optical transmission spectra measurements at 300K. It is shown there is good agreement between the MCT composition and λ_c. The measurement of the curves of the SPR at light illumination from the side of the film surface and from the side of the substrate was carried out. The measurement of the curves of the SPR with the layer by layer chemical etching allows to determine the influence of surface recombination on the SPR curve. Simultaneously the life time of minority carries was measured too by contactless microwave method. This method is based on the automatic microwave measuring at 38 GHz of transient photoconductivity excited by laser pulse ($\lambda \approx 0.92\mu m$) in the temperature range from 80 to 300 K. The maximum radiation power ~ 7W, pulse duration ~ 150 ns and trailing edge duration ~ 7 ns.

The maps of λ_c and life time allows to choose the areas of material on the surface of MCT HS for fabrication of multielements IR-devices (in particular the arrays of linear photoconductivities) with the high uniformity of elements.

ASSESSMENT OF CARBON IN POLYCRYSTALLINE AND MONOCRYSTALLINE GALLIUM ARSENIDE USING SSMS, FTIR, AND CPAA

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The source of C in the liquid B_2O_3 encapsulated Czochralski, vertical Bridgman, or vertical gradient freeze crystal growth of GaAs is ambiguous. C is generally thought to come from the graphit susceptor, the ambient gas, or from the polycrystalline Ga and As, where it is a trace element. Acting as a shallow acceptor, it is one of the key elements in assuring semi-insulating behaviour. In n-type semiconducting material, C is a compensating center, reducing electron density and decreasing the mobility.

Spark source mass spectrometry (SSMS) is a reliable and precise analytical method to measure simultaneously the amount of H, B, C, N, O, Si as well as other trace elements from H to U in GaAs. In favourable cases a detection limit of 1ppb(atomic), which corresponds to $4.43\times10^{13}cm^{-3}$ in GaAs, and a precision of ±5% can be achieved at a trace element concentration level of 50ppb(atomic). For the measurements an upgraded 21-110 high resolution mass spectrometer with multielemental Q plate detection is used. To obtain optimum results the SSMS bulk analysis of GaAs is performed with regard to the effect of sample preparation, evacuation from atmospheric to ultrahigh vacuum pressure below 5×10^{-11}mbar, presparking, collection of series of graded and equivalent exposures from 1×10^{-13}Cb to 1×10^{-6}Cb, mass spectrometric plate processing, computerized optical microphotometric data acquisition, qualitative and quantitative analysis of mass spectra.

For the assessment of C in the bulk of GaAs samples comparable measurements have been carried out using SSMS, Fourier transform infrared spectroscopy (FTIR), and charged particle activation analysis (CPAA) as reference method. New results are presented with the SSMS relative sensivity coefficient $RSC=[C]_{SSMS}/[C]_{CPAA}=3.1\pm0.1$ and the improved appropriate FTIR parameter $f=(7.2\pm0.2)\times10^{15}cm^{-1}$ for the infrared absorption due to the local vibrational mode of C on As site in the GaAs lattice at 77K both calibrated using CPAA. In the concentration range from $2\times10^{14}cm^{-3}$ to $2\times10^{16}cm^{-3}$ the SSMS and the FTIR results are in a rather good agreement for most of the monocrystalline and polycrystalline GaAs samples. In case of different results of the methods it should be noted that the FTIR is sensitive to the electrically active C on As site in the GaAs lattice whereas the SSMS or CPAA is suitable to measure the total content of C in the bulk of the GaAs sample. In polycrystalline GaAs samples the concentration of C can exceed $2\times10^{16}cm^{-3}$, the upper limit of monocrystalline material. In the bulk of such a sample the highest concentration of $3\times10^{17}cm^{-3}$ measured using SSMS is two orders of magnitude higher than the concentration of electrically active C in GaAs measured using FTIR. At this high concentration level C was found additionally in combination with matrix elements. No residual gases, neither hydrocarbons nor H_2O, CO, and N_2 were found in the mass spectra.